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W. W. Ward

Developing, Testing, and Operating Lincoln Experimental Satellites 8 and 9 (LES-8/9)

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FOR THE COMMANDER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

DEVELOPING, TESTING, AND OPERATING LINCOLN EXPERIMENTAL SATELLITES 8 AND 9 (LES-8/9)

W. W. WARD
Group 68

TECHNICAL NOTE 1979-3

16 JANUARY 1979

LEXINGTON MASSACHUSETTS

ABSTRACT

This report presents a number of sidelights on the development, testing, and operation in orbit of Lincoln Experimental Satellites 8 and 9 (LES-8/9). The details of these matters have been published elsewhere. Significant factors contributing to the success of the LES-8/9 program (terminals as well as satellites) are identified.

This paper was presented at EASCON-78, Arlington, Virginia, on 1978 September 27.

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I. INTRODUCTION AND SUMMARY

Lincoln Experimental Satellites 8 and 9 (LES-8/9) began life as transformations of the basic LES-7 spacecraft design, with communications payloads operating both in the military UHF band and at K-band. They were developed with the goal of demonstrating, in full-scale operation (terminals as well as satellites), advanced technologies for strategic communications links. This goal has been achieved, and the technologies have been transferred to Industry. Most of these advances are applicable to civil as well as to military space communications.

Looking back over the LES-8/9 program, one can draw instructive lessons from its progress as hard problems arose and difficult decisions were made. For example, a challenging project at the technological frontier (optical crosslinks between LES-8 and LES-9) was dropped so that the available resources could be concentrated on more practicable tasks (the very successful K-band crosslinks, for example). The procurement of reliable components was a major problem (and remains so). Functional integration of LES-8/9 with ERDA-provided radioisotope thermoelectric generators (RTGs) as the sources of electrical power in orbit presented difficulties, particularly in terms of compatibility among the individual payloads (LES-8/9 and SOLRAD-11A/B) comprising the P74-1 launch under the SAMSO Space Test Program. These and many other barriers were successfully surmounted during a lengthy, exhaustive, program of pre-launch testing. After a beautiful launch aboard a Titan III-C, LES-8/9 and their terminals began a complex program of post-launch testing and demonstrations which was completed ahead of schedule. Unique facilities were developed for telemetry/command management of the satellite resources from the Lincoln Experimental Satellite Operations Center (LESOC) in Lexington, Massachusetts. Specialized equipment devoted to telemetry/command management of the LES-8/9 communications payloads has been routinely operated from user command-post terminals (including an AFAL airborne terminal).

The results of the LES-8/9 Joint Test Program have been published, and the satellites have entered what is expected to be a long period of useful service to the Government as residual communications assets. The complexity of their internal architecture has proved to have benefits above and beyond the realization of the advanced communications links that were tested. It has been possible to work around the few problems that have arisen during 2+ years in orbit, by virtue of redundancies and alternatives built into the on-board systems. Moreover, continued acquaintance with these satellites has shown that they have novel, fruitful, capabilities; functions inherent in their design but not consciously anticipated. Both satellites continue in excellent health, with every indication of providing many years of useful service.

II. SYSTEM DESIGN

LES-8/9 and their associated communications terminals were developed to demonstrate technologies applicable to strategic command-and-control communications (C^3) systems (Ref. 1). The emphasis throughout was on hard (i.e., anti-jam, survivable) low-data-rate links between command posts and force elements and moderate-data-rate links among command posts, any or all of which terminals might be mobile. The system design of these integrated links has been reviewed elsewhere (Ref. 2). The technical considerations led to links operating in the military UHF band (225-400 MHz) and in the EHF band (K-band, 36-38 GHz) (Fig. 1).

Most of the advances demonstrated by LES-8/9 are applicable to civil as well as to military space communication. For example, LES-8/9's millimeter-wavelength satellite-to-satellite crosslinks, providing extended-area coverage without intermediate ground relay stations, are the archetypes of similar crosslinks, operable at microwave or even optical wavelengths, that will carry traffic in the INTELSAT domain when the demand justifies them. More immediately, the LES-8/9 crosslinks make it practical to manage (telemetry monitoring, command actuation), via intermediate-satellite relay,

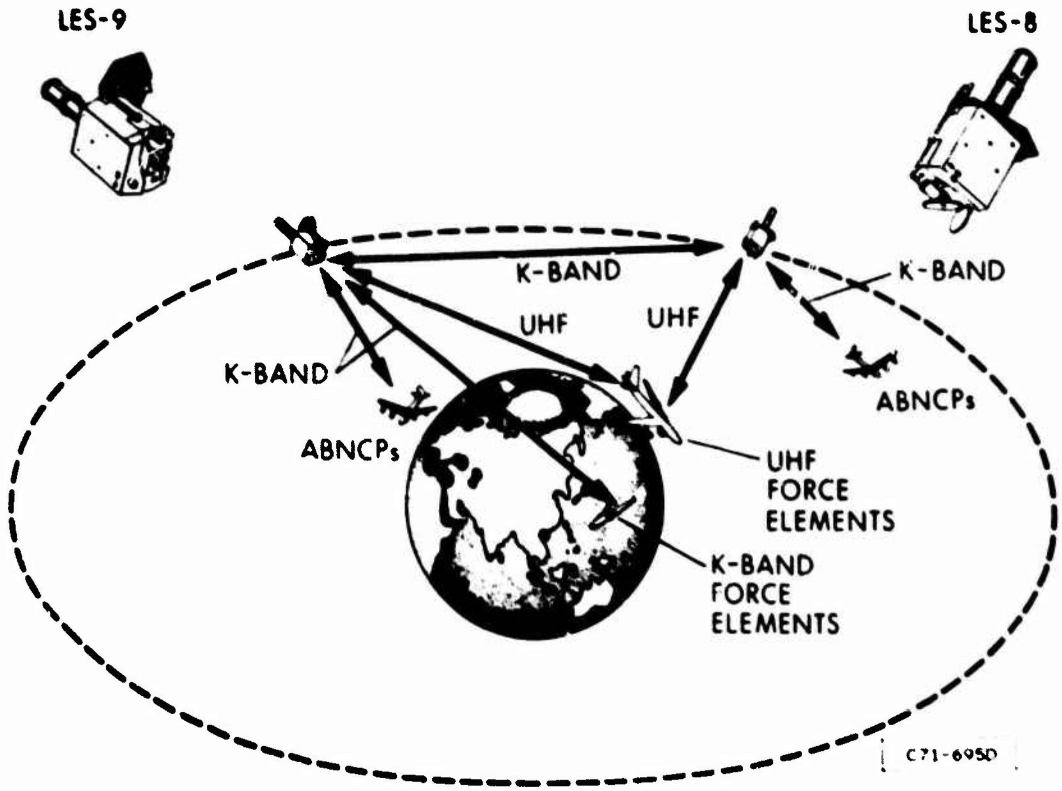

Fig. 1. LES-8 and LES-9 communications configuration.

a spacecraft that is out-of-sight of the control center. NASA's tracking and data-relay satellite system (TDRSS) is being established for just such an application.

III. CONFIGURATION

LES-8 and LES-9 began as transformations of the basic LES-7 spacecraft. That design for a solar-powered satellite (Fig. 2) used three-axis stabilization with the antennas and primary sensors facing the Earth. The decision to power LES-8/9 with RTGs was easily accommodated; the end of the spacecraft facing away from the Earth was an obvious place to put them. The thrusters for orbit and attitude control remained on the east and west faces of the spacecraft. The Earth-facing end became rather crowded, however (Fig. 3). In the early stages of design, LES-8/9 carried both EHF and optical crosslinks.

Figure 3 suffers from several deficiencies, principally the absence of a UHF antenna system. The first attempt (Fig. 4) to remedy that shortcoming was not satisfactory. Novel approaches were considered, such as Fig. 5. Fig. 6 shows another preliminary configuration concept (without a UHF antenna system, however). In several significant respects it foreshadows the final design. By the time Fig. 7 was drawn, the UHF antenna system had developed into three cavity-backed spiral elements (to provide the circularly polarized radiation required to avoid the Faraday-rotation-effect problems that beset linearly polarized UHF radiation as it propagates through the ionosphere).

The final configuration of LES-8/9 (Figs. 8 and 9) resulted from many difficult decisions. It can be seen that the UHF antenna system has jelled as three crossed dipoles over a ground plane, cantilevered out to look past the body of the spacecraft toward Earth. The orbit planes of LES-8/9 have become near-ecliptic (Sec. IX), allowing the use of optical solar reflectors (OSRs) to radiate internally dissipated power out the north and south faces as heat. The optical crosslink disappeared after it became clear, late in 1971, that LL's available resources were spread too thin to do justice to two

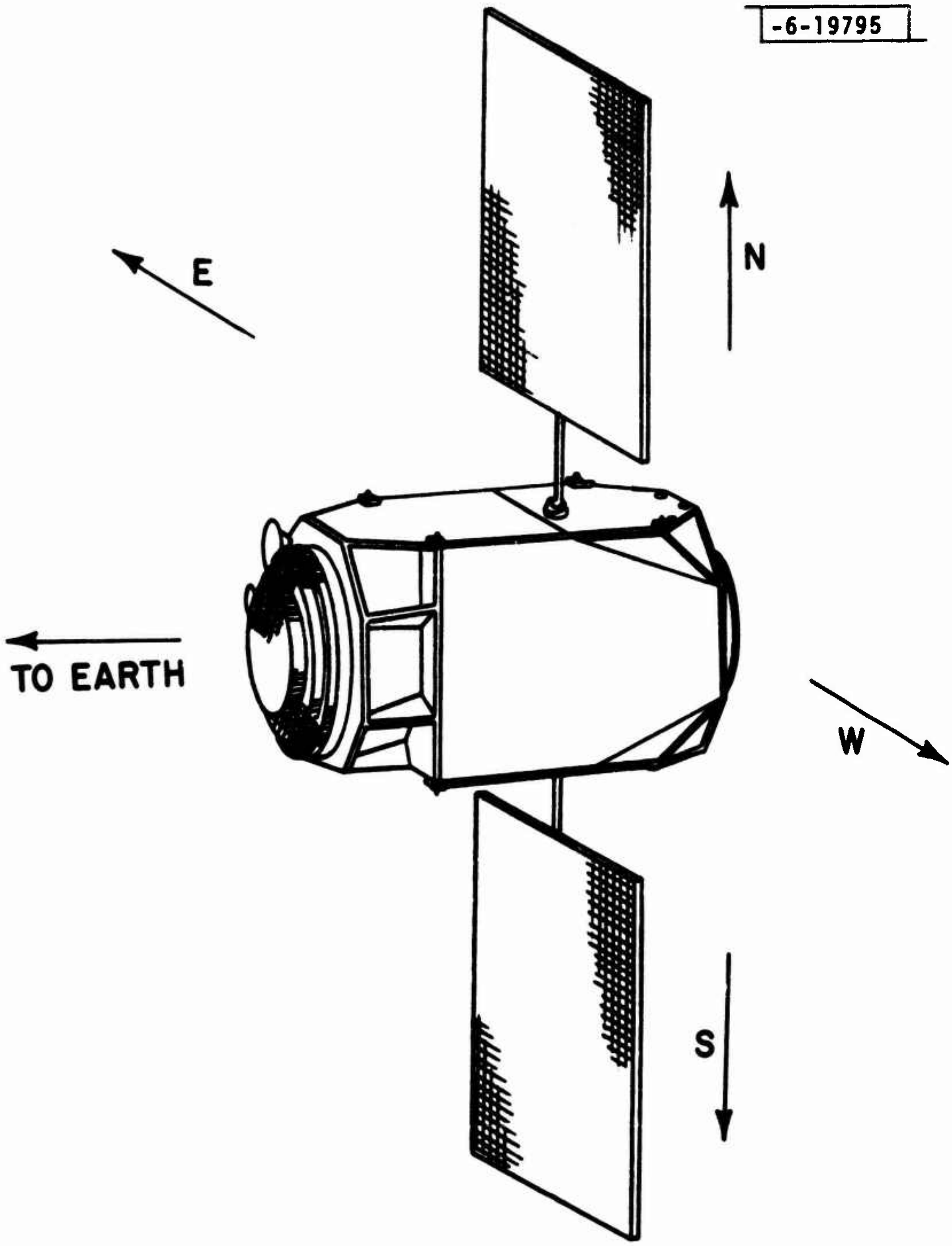

Fig. 2. Design study for LES-7.

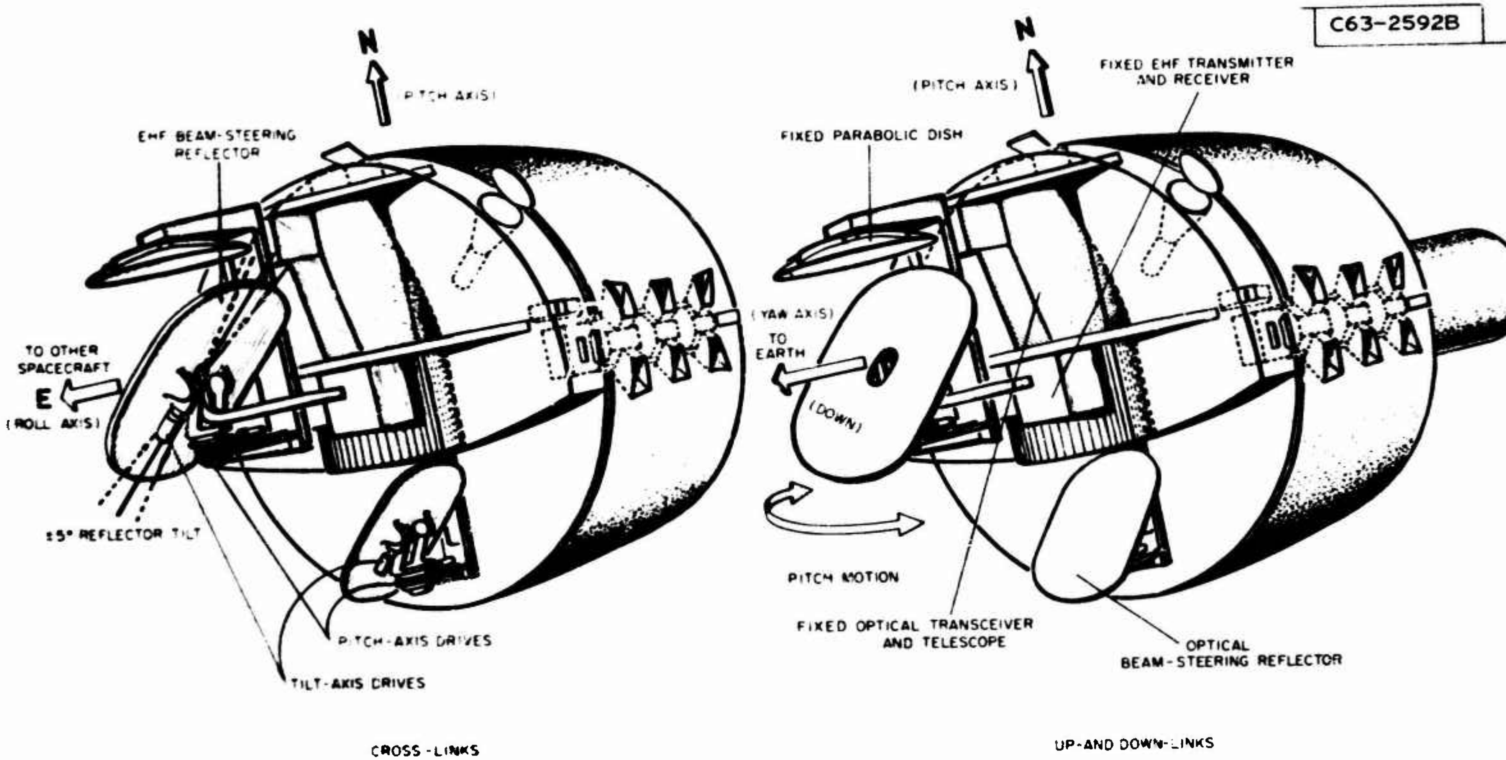

Fig. 3. Design study for LES-8/9 EHF and optical crosslinks (UHF provisions not shown).

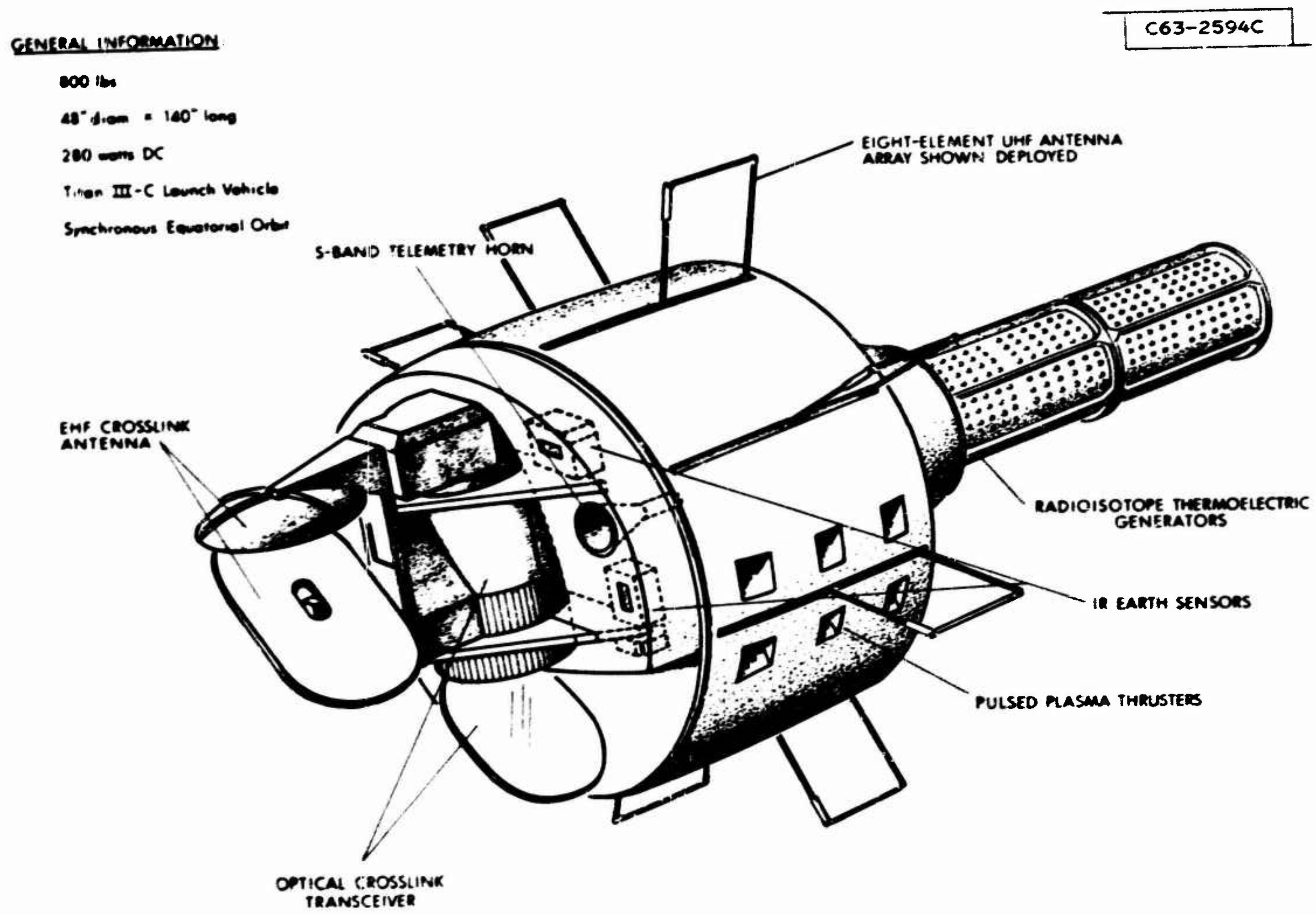

Fig. 4. An early LES-8 and LES-9 configuration.

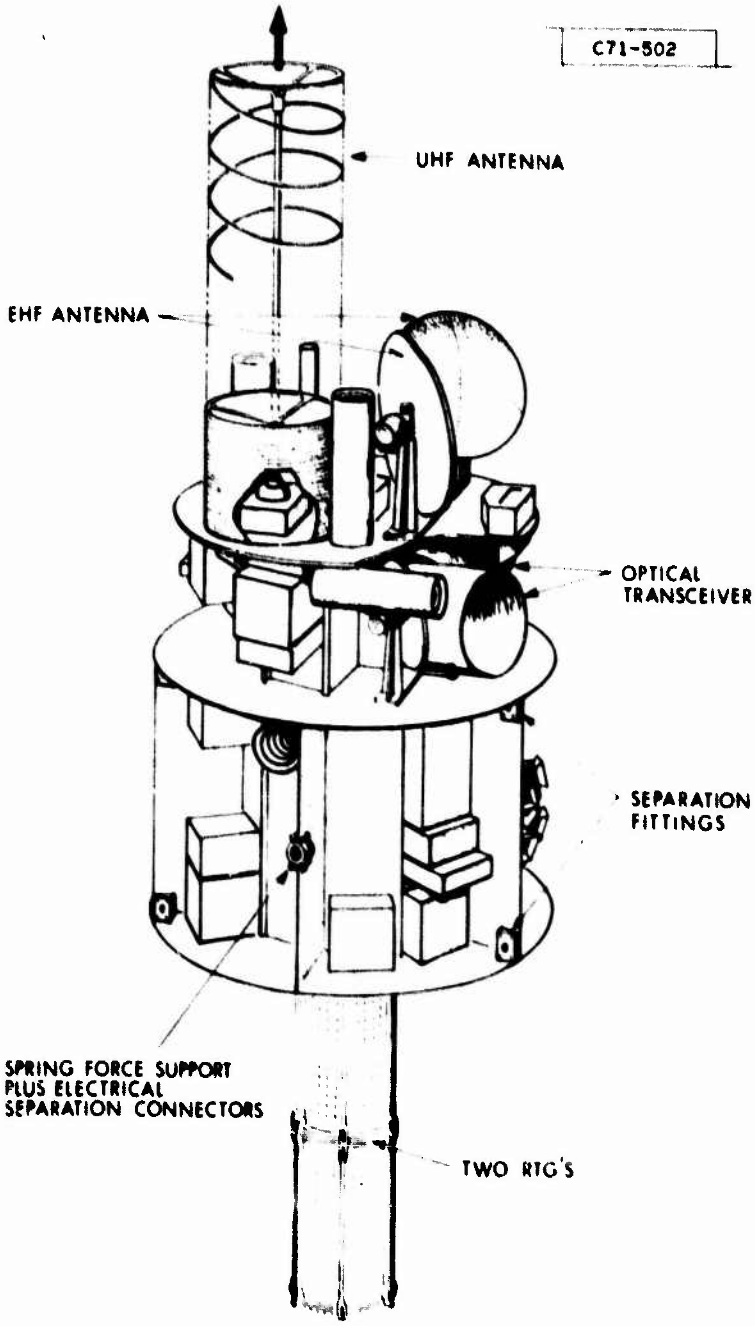

Fig. 5. An alternative configuration for LES-8 and LES-9.

kinds of crosslinks*. This decision was a disappointment at the time, but it was inevitable.

The pulsed plasma thrusters (PPTs) were exchanged for cold-ammonia gas-propulsion sub-systems (GPSSs). The feasibility of PPTs for spacecraft propulsion was not in question. The situation was that, during testing, the LES-8/9 PPTs failed to reach a level of consistently successful performance that would give confidence in their reliability (Ref. 3). The TRW-built GPSSs that were ultimately flown (Ref. 4) did not represent an advance in the state-of-the-art; they simply worked.

There was one practical benefit for LES-8/9 from the engagement with PPTs. A great deal of care was taken in fabricating and testing electronic boxes and cabling to make sure that they would not be affected by RFI from the high-voltage arc discharges and other phenomena in the PPTs. Those approaches served as the starting point for general precautions to mitigate the effects of orbital charging (Refs. 5, 6). In that connection, the standard practices of box fabrication, inter-unit cabling, etc., used on Lincoln Experimental Satellites yield equipment that is inherently resistant to transient-discharge effects.

In two areas, transient discharges related to orbital-charging effects are to be expected for LES-8/9:

(a) The quartz OSRs (second-surface mirrors) could accumulate charge on their outer surfaces, leading to tree-like arc discharges among the tiles. Vendors of OSRs were developing mitigation techniques for their products, but evaluating and qualifying the proposed remedies might have been a lengthy task. Besides, we had already invested in a full kit of OSRs for both satellites. Laboratory tests had shown that transient discharges did not degrade the optical quality of the OSRs.

*The state-of-the-art in laser-diode technology and its application (as proposed for the optical crosslink) at that time made this an extremely high-risk enterprise as well.

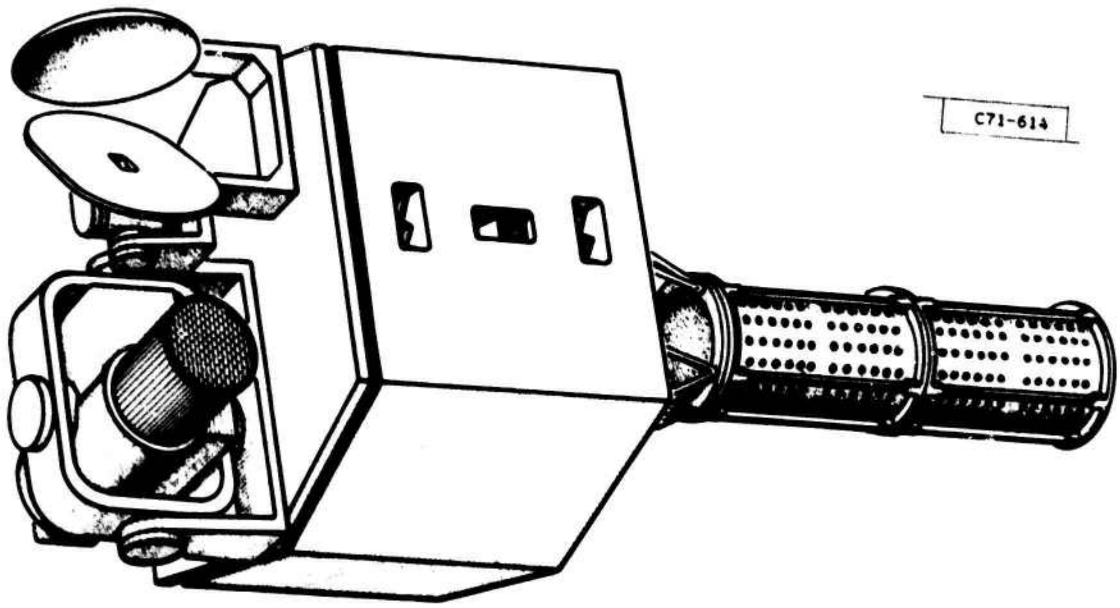

Fig. 6. Design study for LES-8 and LES-9 (UHF provisions not shown).

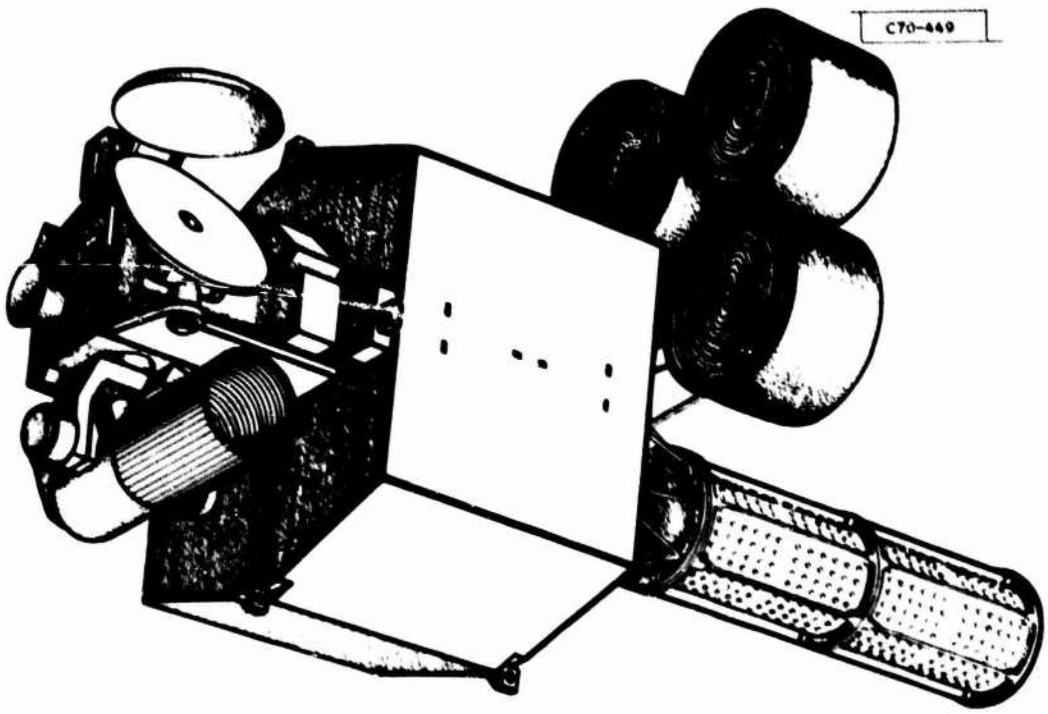

Fig. 7. Candidate configuration for LES-8 and LES-9.

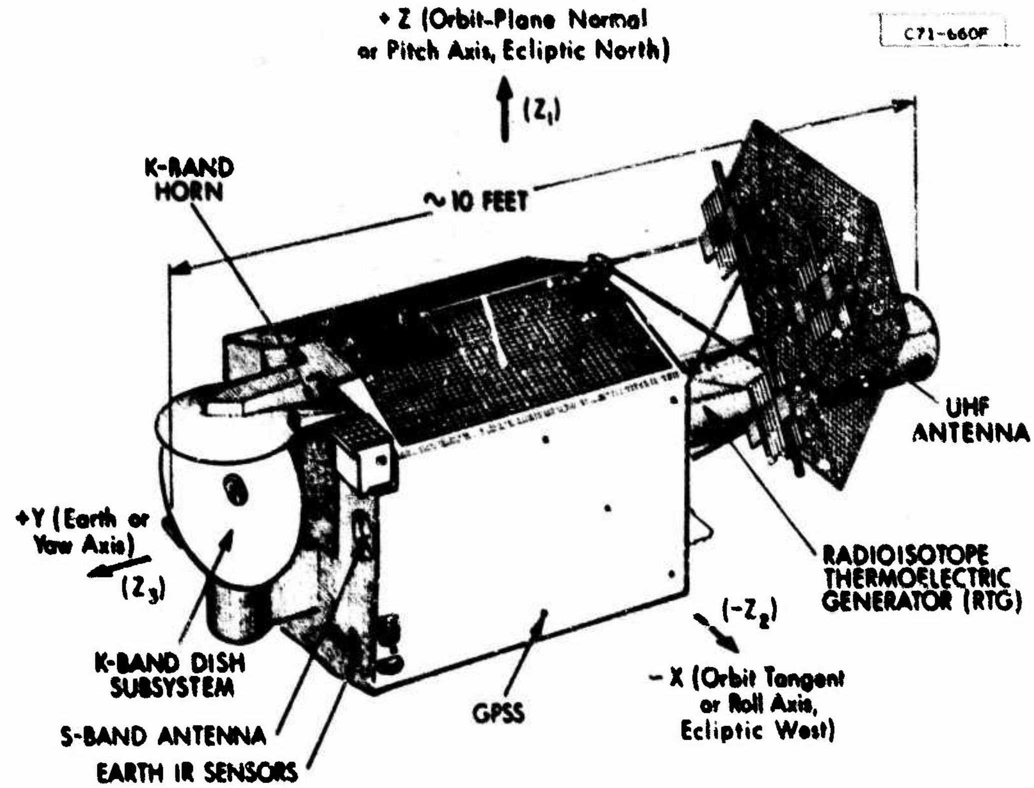

Fig. 8. Illustrated arrangement LES-9 (flight configuration).

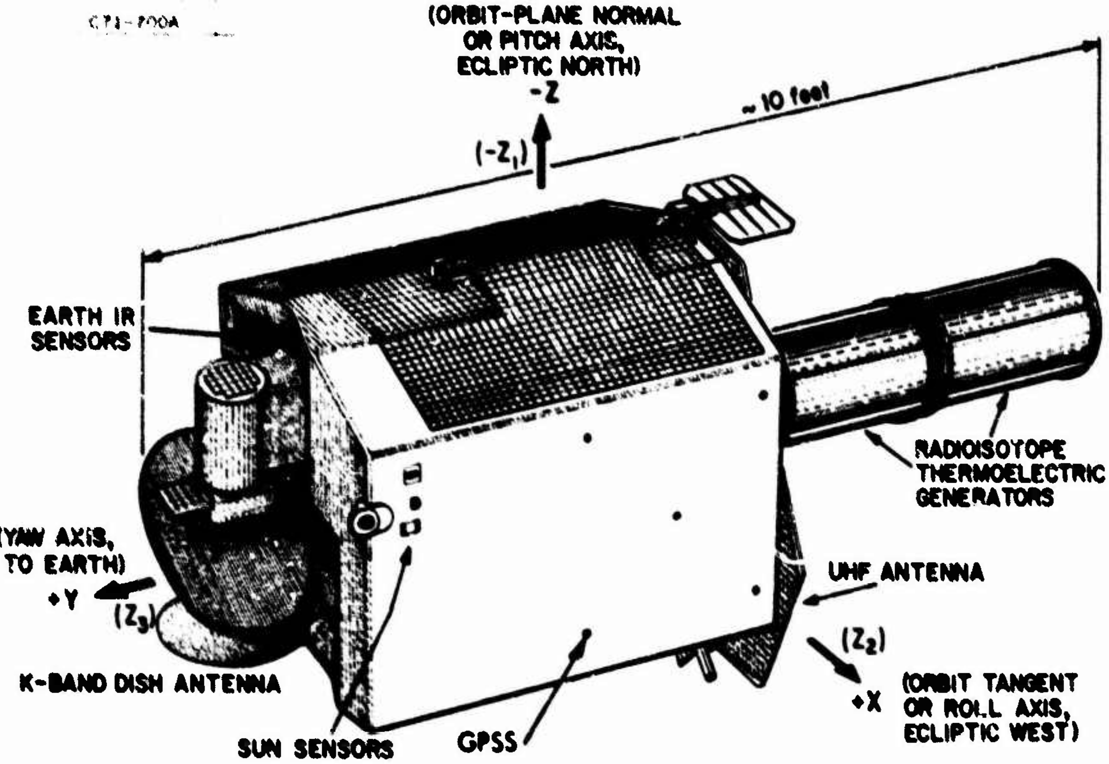

Fig. 9. Illustrated arrangement LES-8 (flight configuration).

(b) The kapton thermal-blanket material, when shadowed, could accumulate charge on its dielectric outer surface. We had no remedy for that problem. When the kapton was in sunlight, the bulk photoconductivity (together with ground straps to the layers of metallization in the thermal blankets) would drain charge away.

Thermal-vacuum tests indicated that neither of these situations produced significant problems for the LES-8/9 communications and housekeeping systems, so LES-8/9 were launched with conscious acceptance of them. The successful operation of these satellites in orbit has vindicated that forced decision.

LES-8/9, while not absolutely identical, are close to it, being functionally interchangeable in most respects. It can be seen from Figs. 8 and 9 that the satellites are rotated 180° in yaw (about the Earth-pointing axis) from each other. The satellites were nested aboard the Titan III-C Transtage in the same way (Fig. 10).

The choice of K-band (36 - 38 GHz) for the crosslinks deserves comment. In the original conception of LES-8/9, the EHF crosslinks were to be at V-band ($\sim$55 GHz). The frequency choice was on the lower edge of the oxygen absorption region, which offers a significant amount of privacy from interception and immunity from jamming (hostile terminals assumed to be within the Earth's atmosphere). It soon became apparent that the 1971-era technology would not support such an enterprise. The basic problems met in developing the transmitter and receiver components are much the same at V-band and at somewhat lower frequencies, though fabrication techniques are undeniably simpler at the longer wavelengths. In the case of LES-8/9 crosslinks, there was very little commercially available test equipment above 40 GHz. So, it was decided to build the crosslinks and the EHF up- and downlinks in the same 36-38-GHz region, called K-band here (Ref. 7). It is thus possible to utilize the crosslink antennas for uplink and downlink service (instead of the horn antennas) when the higher link margins which they afford are advantageous.

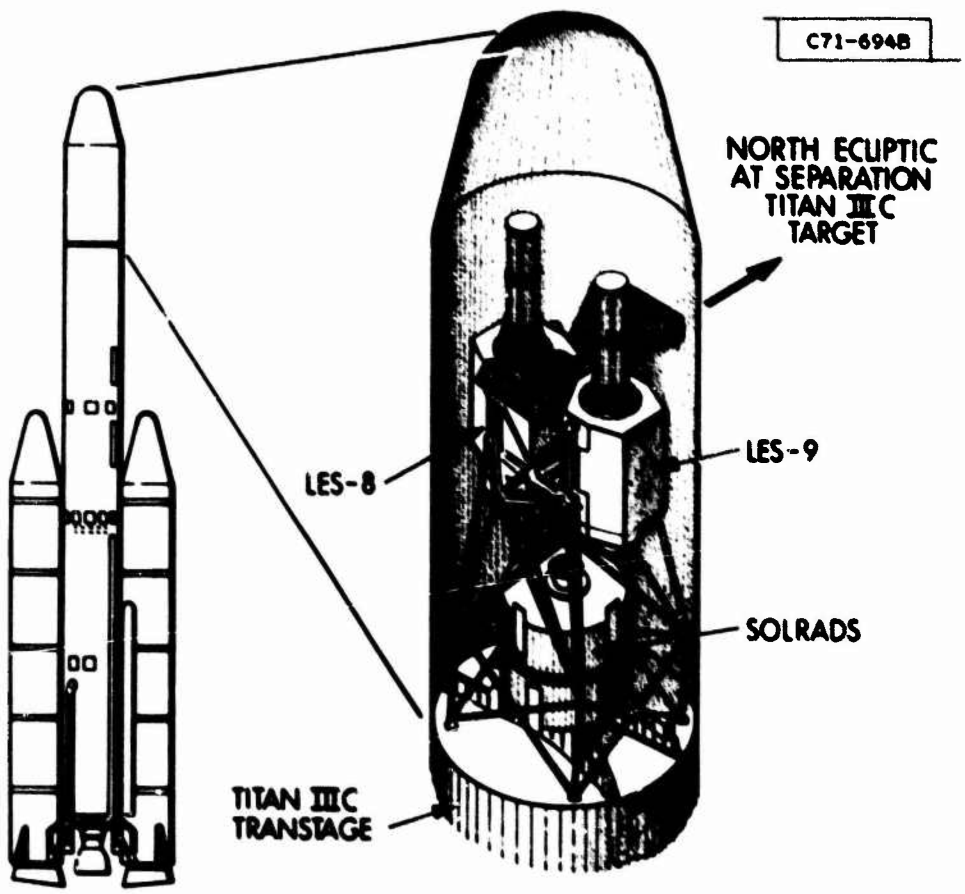

Fig. 10. TITAN III-C launch vehicle and P74-1 payload.

The frequency allocation for these links was obtained on an experimental basis. Looking at the situation in 1978, it should be easier to put the cross-links in the 55-to-65-GHz region, although the technology would continue to present challenges. The EHF up- and downlinks might be placed in suitable frequency allocations above 40 GHz.

A summary of the characteristics of LES-8/9 is given in Tables 1 and 2. Figure 11 gives a simplified representation of the satellite systems and sub-systems. The justification for the development and launch of LES-8/9 lay in the advanced communications system (above the dashed line). The unique character of certain systems below the dashed line made it necessary for LL to take charge of the housekeeping systems also. A great many industrial contractors contributed piece parts, components, and sub-systems to LES-8/9. The responsibility for their design, integration, pre-launch testing, and operation in orbit lay with LL.

TABLE 1

LES-8/9 PROGRAM

SPACECRAFT

- ~ 1000 lb (mass) EACH
- 3-AXIS-STABILIZED TO EARTH
- CIRCULAR, SYNCHRONOUS, NEAR-ECLIPTIC COPLANAR ORBITS
- RTG POWER SUPPLIES
- K-BAND/UHF COMMUNICATIONS
- SPACECRAFT-TO-SPACECRAFT CROSS-LINKING (K-band)
- FLEXIBLE ON-BOARD SIGNAL-PROCESSING
- SPREAD SPECTRUM (frequency-hopping) FOR ANTI-JAM
- AUTONOMOUS ATTITUDE CONTROL AND STATIONKEEPING
- COLD-GAS (ammonia) ON-BOARD PROPULSION
- COMPREHENSIVE TELEMETRY AND COMMAND

TERMINALS

- LL AIRBORNE-COMMAND-POST TERMINAL – 4-ft ANTENNA (K-band)
- LL SHIP REPORT-BACK TERMINAL – 18-in. ANTENNA (K-band)
- LL FORCE-ELEMENT TERMINALS (UHF)
- AIR FORCE AND NAVY TERMINALS (K-band, UHF)
- LESOC, LEXINGTON

TABLE 2

RF SYSTEMS OF LES-8/9

Satellite-to-Satellite Cross-Orbit Links

Uplinks and Downlinks

K-Band (36 – 38 GHz)

- 0.5 W RF
- 25 dBi gain – Earth-link horn antenna
- 42 dBi gain – cross-link dish antenna
- 1700°K T_{sys}

UHF (225 – 400 MHz)

- 8/30 W RF
- 8.5 dBi gain – Earth-link antenna
- 1000°K T_{sys}

On-Board Signal Processing

Bandspreading for Anti-Jam

500-kHz UHF-to-UHF Translation Mode

S-band (∿ 2.2 GHz) Telemetry Downlink

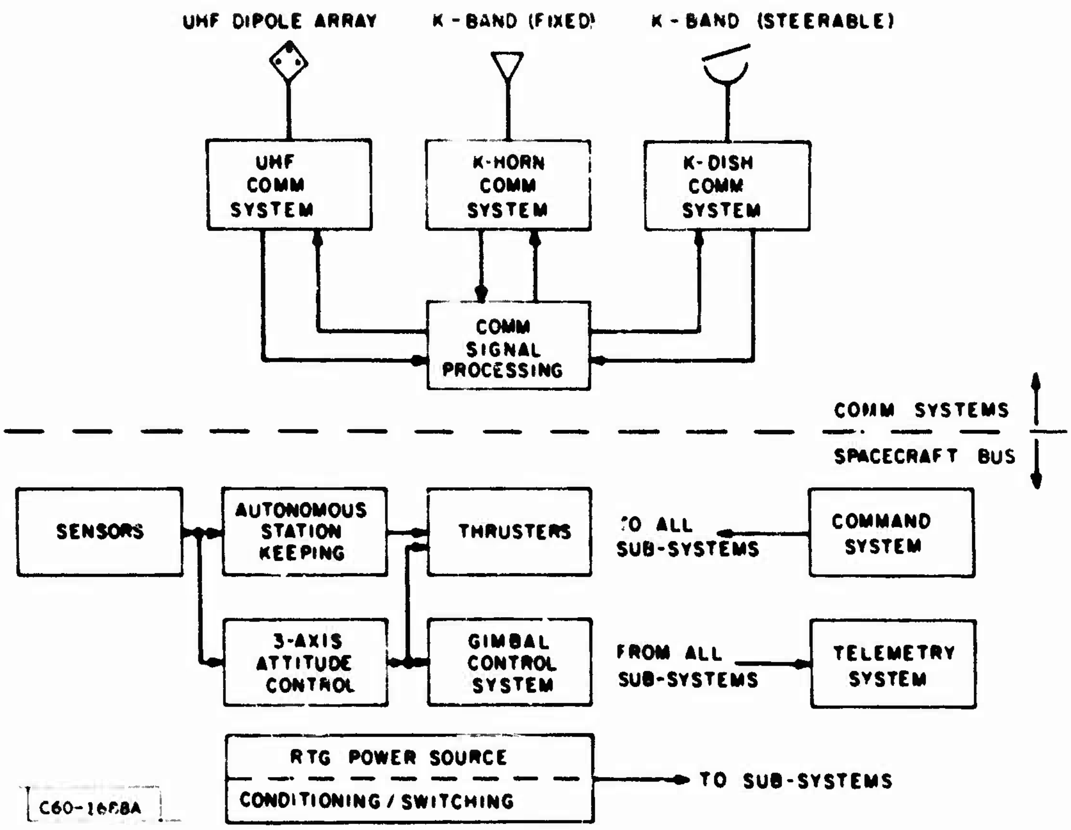

Fig. 11. LES-8/9 simplified.

IV. COMPONENTS AND TESTING

The most vexing single problem area that was met during the development of LES-8/9 was the procurement of reliable components in needed quantities. The complexity of the on-board systems for signal-processing and autonomous housekeeping functions required large numbers of high-quality semiconductor devices (digital logic circuits, microwave diodes, etc.), not to mention relays for DC, IF, and RF signals. An approximate electronic-parts count for either satellite is given in Table 3.

TABLE 3

APPROXIMATE ELECTRONIC-PARTS COUNT FOR LES-8 OR LES-9

Integrated circuits	4700
Transistors	3700
Diodes	2800
Relays	100
Resistors	5100
Capacitors	10,700
Inductors	150
Total	27,300

It was extremely difficult to motivate some suppliers to meet our needs. In terms of dollars, our orders were trifling alongside their other business. Our determination to get good devices (extending to the point of monitoring production-line practices) occasionally led to strained relations. There was no other way to handle the problem. It would not be much easier to handle it today. All the steps of fabrication and inspection that yield high-quality components can be written down and put into MIL standards (Ref. 8). The rub comes in motivating (or enforcing) dedicated compliance by the supplier.

Somehow, enough flight-quality devices were obtained to build the two satellites. Testing at the PC-board level was enlivened by the discovery that the pressure level originally used during the testing of ICs for leaks was inducing leaks. There were very few component failures during the extended period of pre-launch testing after spacecraft integration. The continued successful operation of LES-8/9 in orbit, more than two years after launch, is abundant justification for the rigorous inspection and test measures that were taken.

One can have confidence in the successful performance of a payload of any desired degree of complexity provided one makes the requisite investments of:

(1) Care in system design (including provision of alternatives to be invoked if and when failures occur),

(2) Implacable dedication to quality in fabricating and procuring components and sub-systems, and

(3) Inexhaustible diligence in testing the flight systems, not letting any instances of singular behavior go unexplained.

The importance of pre-launch system testing over a wide temperature range cannot be overstated. The state-of-the-art in the design and pre-launch testing of thermal-control systems makes possible the prediction of box temperatures in orbit to within, say, ± 10°C (Ref. 9). One level of product assurance (common in Industry) consists of testing the box over its expected temperature range with 10°C-or-so extensions on each end. That is, a box which is expected to run between +10° and +25°C in orbit is tested in operation over 0° to +35°C. Lincoln Laboratory subjects its flight boxes (as well as the complete systems comprising them) to spec-performance operating tests over much wider temperature ranges. In the case of the communications-system payloads for LES-8/9, there were repeated test runs (in air) between -40° and +60°C in 20°C increments. Housekeeping systems (with the exception of units such as the gimbaled momentum wheel) were tested similarly between -60°C and +80°C. These rigorous tests smoked out marginal circuit designs and interface conditions. Faulty components that had not been caught in the parts screening failed. Deficiencies in workmanship (solder joints, for example) showed up as the thermal cycling continued. It might have been feared that we would wear the payloads out while testing them, but a prudent balance was struck. The subsequent thermal-vacuum testing of the complete satellites was relatively uneventful from a reliability point-of-view; almost all the problems had already been found and fixed. The primary purpose of the thermal-vacuum testing (which was not a stress test) was the verification of the performance of the LES-8/9 thermal-control system in the closest simulation of the flight environment that we could provide.

Some people think that Lincoln Laboratory overdoes the testing bit, perhaps revealing masochistic compulsions. Some people say that their programs could not possibly afford so much testing, in either time or money. It often happens, however, that the post-mortem inquiry on the failure of a spacecraft mission reveals glaring deficiencies in pre-launch testing, sometimes coupled with negligence in studying and interpreting the results of whatever testing was done. A failure of that sort is something that no one can afford.

The pre-launch test program was greatly facilitated by the availability throughout all LES-8/9 systems and sub-systems of extensive, instrument-quality, telemetry provisions (Refs. 10, 11). The telemetry listing for each satellite contains more than 1,000 line items; from single data bits that tell the positions of commandable switches to A/D-converted measurables such as temperature, current, RF power, etc. The 0-to-6.5-V range for telemetered voltage signals is divided into 1.6-mV steps for 12-data-bit telemetry words. Dual-range A/D conversion and encoding makes available 0.2-mV and 3.2-mV step sizes, so a very wide dynamic range can be accommodated faithfully where required. Considerable effort was expanded to make this telemetry system (particularly its input transducers) believable over the usual LL extra-wide range of operating temperatures during testing. When a fractional-percent variation in some measured quantity shows up in the telemetered data, it is real. Such indications often led the pre-launch testers to discover and fix problems that would have been masked by a coarser telemetry system.

The command listing for each satellite includes more than 400 line items, from sending single data bits to change the positions of commandable switches to transmitting strings of data bits which, for example, can specify updated pointing positions for search and acquisition in angle by the biaxial crosslink drive (BCD). The flexibility afforded by this versatile command structure has made it possible to work around the few failures that have occurred in orbit and to maintain all spacecraft functions available for use, throughout the Joint Test Program and afterwards.

As the pre-launch test program progressed, flight-like telemetry and command functions became predominant in the all-up and end-to-end testing of housekeeping and communications systems. Engineers were weaned from dependence on non-flight-like measuring means such as clip leads. When it came, the transition to actual orbital operations was comparatively simple, for most functional interfacing with the satellites had already been by means of their telemetry and command systems for some time.

V. COMMUNICATIONS-LINK TESTING

One of the strengths of LL's program in space communications has been that it encompasses the development of both terminals and satellites (thus, the whole system) under the same roof. In the case of the LES-8/9 program, this factor was indispensable. Transmission and reception for satellite links providing substantial AJ capability are indisputably complex by comparison with simple links through unprotected transponders. It would be extraordinarily difficult to develop separately (and successfully) the space and terrestrial segments of a modern space communications system (Fig. 12, for example) if their first operating encounter were only after launch.

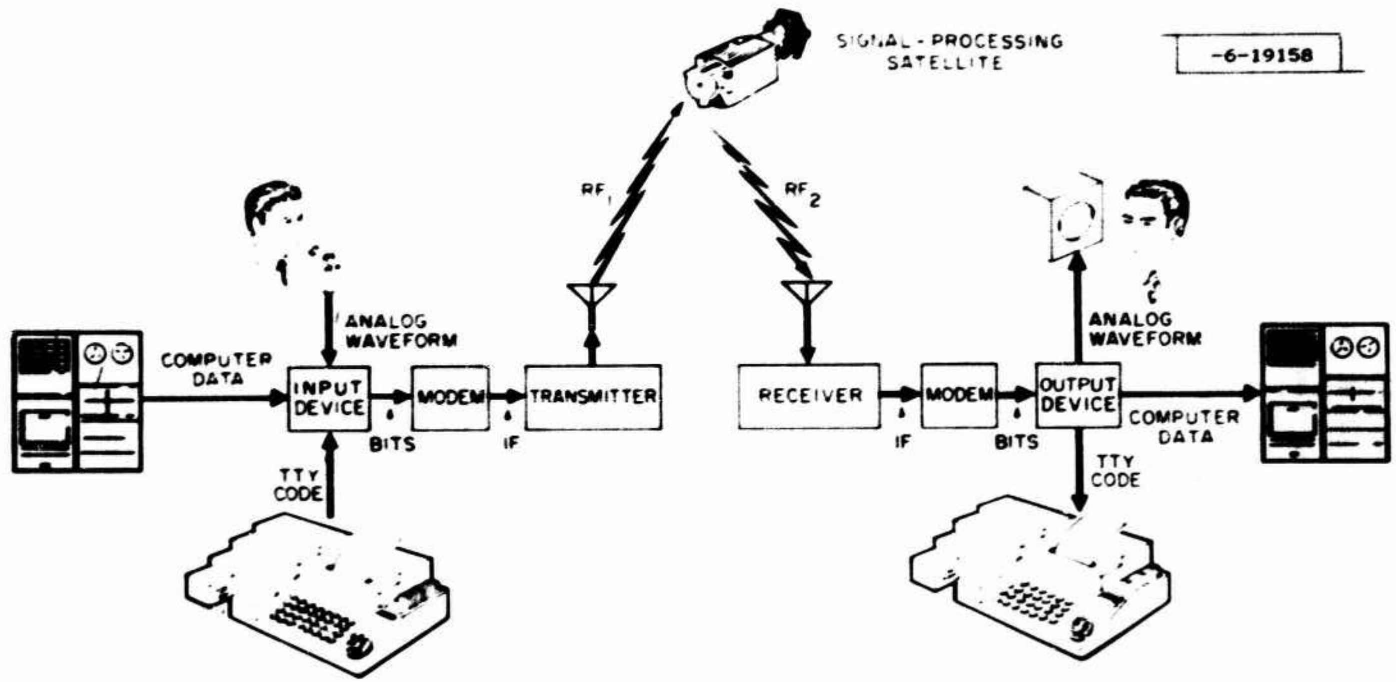

Fig. 12. A modern space-communications system.

Communications-link testing at LL began while both the satellites and the terminals were in breadboard/prototype phases. As flight-quality satellite hardware became available, such boxes replaced less-worthy ones in the test chambers, allowing the environmental testing to attain its full rigor (Sec. IV). Much of the testing was carried out using a computer-controlled automatic test system (ATS). When enough confidence had been gained in the integrity of the test setup, making unattended overnight thermal runs became a routine procedure. Initially, the LL-built terminals (in breadboard form) were located in a room adjacent to the test chambers. As the actual prototype terminals came into being in a penthouse atop one of the Laboratory buildings, RF links were established between the satellites and the terminals (Fig. 13). This Figure shows a representative test setup, in which the LL Navy mast terminal can communicate with the LL ABNCP terminal either via a single satellite or (using the crosslink) via both of them.

It was especially fortunate that the Service terminals were able to visit Lexington for compatibility tests with the actual satellites before the satellites were shipped to Cape Canaveral. There had already been substantial, effective, technology-transfer interaction between LL, the Service Laboratories, and Industry. However, the actual tests at Lexington disclosed a few areas in which misunderstanding and misinterpretation had allowed interface problems to arise. With both ends of the link and the satellite(s) all in the same location, it was a relatively straightforward task to uncover such problems, resolve any ambiguities, and fix the troubles. The generally smooth course of the Services' communications-link testing in orbit owes a great deal to these pre-launch tests at Lexington.

While it is not intended to review the detailed quantitative results of the on-orbit communications-link tests (Ref. 12) here, the over-all conclusion is worth stating. There were no surprises. The links worked as they should, the results of both pre- and post-launch tests agreeing closely with each other and with the theoretical results of analysis and computer simulation.

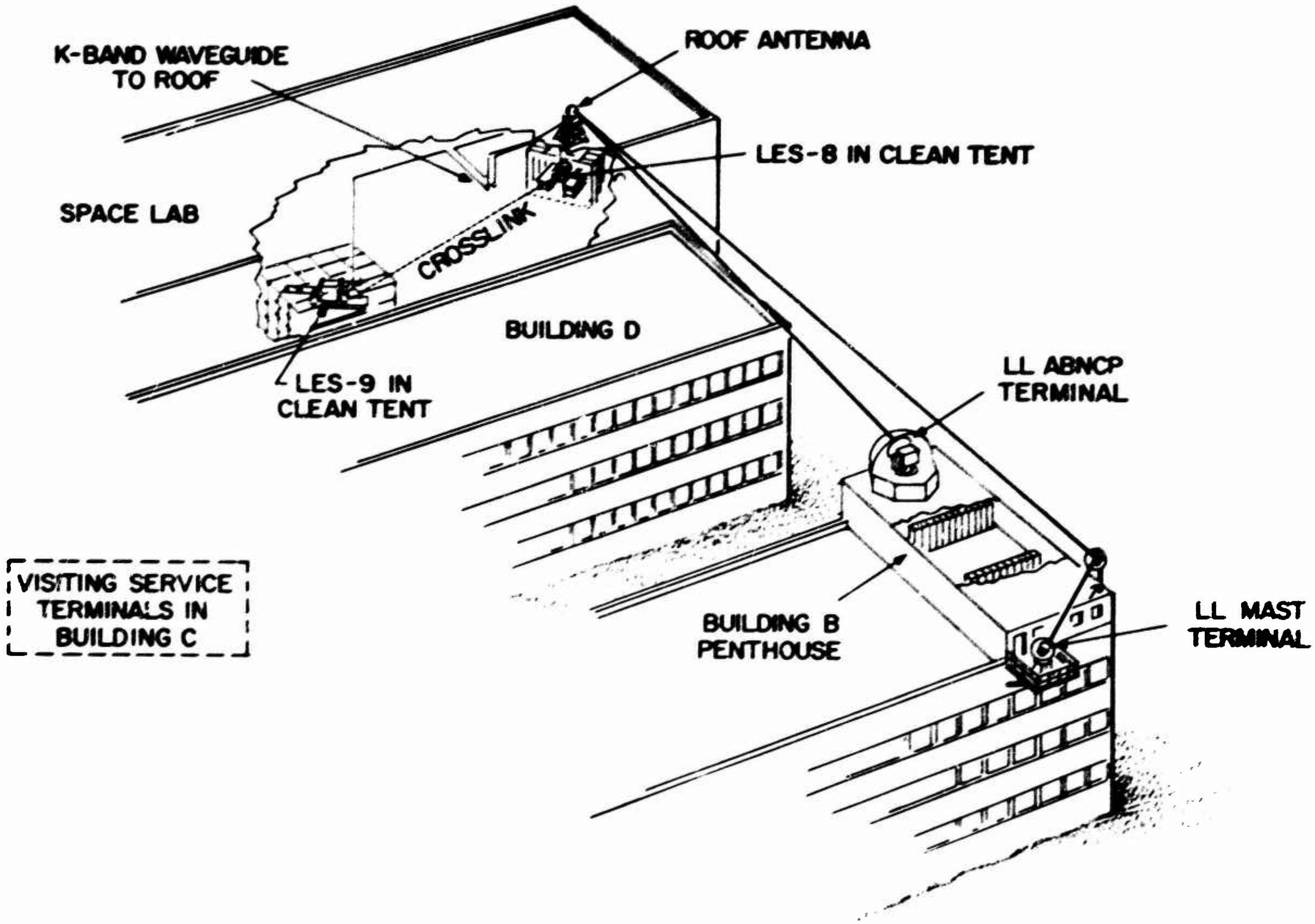

Fig. 13. [illegible] and [illegible] communication terminal before launch.

When user requirements demand it, one can move with confidence into new areas of communications-system application on the basis of three cardinal principles:

(a) To begin with, base the work on sound system analysis and design,

(b) Give painstaking attention to details great and small during the fabrication of the hardware and the generation of the software, and

(c) Finally, carry out thorough, rigorous pre-launch system testing, to establish that the goals of (a) have been closely approached and that any failings under (b) have probably been uncovered and dealt with.

VI. CLEANLINESS AND HANDLING

LES-8/9 were constructed with particular attention to the cleanliness of parts and people. Rigorous quality-control procedures were established for handling components, fabricating subassemblies, and integrating the flight spacecraft. It is believed that the faithful implementation of these procedures by the LL work force has contributed substantially to the satellites' success in orbit. They carried along few (if any) loose washers, insulation strippings, etc.

Integration of the flight payload in the Spacecraft Assembly Building (SAB) at Cape Canaveral presented novel problems. LES-8/9 (including their RTGs) were first mounted on the payload support structure (truss) in the SAB (Fig. 14). The truss was supplied by TRW Systems, the payload-integration contractor for the P74-1 mission (Ref. 13). The Titan III-C fairing was then lowered over the assembly, encapsulating it for the trip to the pad (Launch Complex 40, about 7 miles away). The catch was that it was absolutely essential to supply the aluminum fairing with large quantities of clean, cold, dry air from that time until launch, since the 4 RTGs (on the 2 satellites) produced a total heat output of 10 kW. Continuity of air flow into the fairing was maintained during the trip and the lift up the gantry (Fig. 15), the lowering onto the Titan III-C Transtage (to which

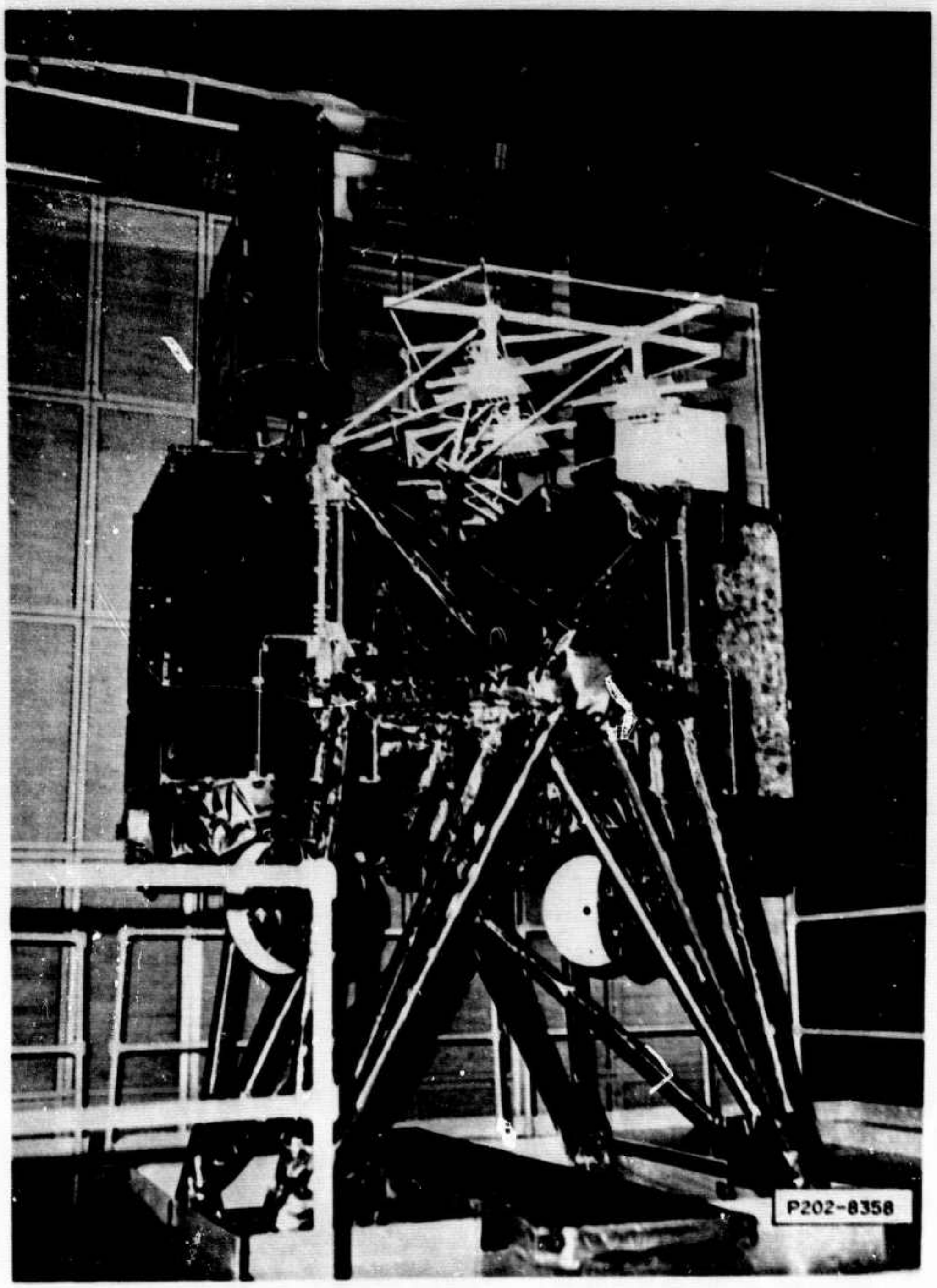

Fig. 14. LES-8 and LES-9 at the Cape. LES-8 (left) and LES-9 (right) integrated on the payload support truss in the Spacecraft Assembly Building (SAB) at Cape Canaveral, Florida, on 17 February 1976.

Fig. 15. Lifting LES-8/9 up the gantry at Launch Complex 40, Cape Canaveral, Florida, on 24-25 February 1976.

NRL's SOLRAD-11A/B spacecraft had already been integrated), and the 17-day delay before launch (Fig. 16).

VII. ORBITAL OPERATIONS

LES-8/9 were launched by the same Titan III-C booster, built by Martin-Marietta. The guidance system had problems ahead of time, necessitating launch delays, but its ultimate performance was superb. LES-8/9 were put into orbit by the final Transtage burn under very nearly nominal conditions. A portion of the GPSS fuel had been budgeted for possible expenditure in attaining the desired orbits, assuming under- or over-performance of the booster. It was not necessary to tap this reserve significantly, so it remains available to extend the satellites' useful lives.

After final orbital injection near the longitude of Lexington on 1976 March 15, the satellites were dispensed by the Transtage, LES-8 at $\sim$ 1.5 ft/sec to the west, LES-9 at $\sim$ 1.5 ft/sec to the east (Fig. 17). It followed from the laws of orbital mechanics that LES-8 began to drift eastward, LES-9 westward (a well-known apparent paradox). Within 5 hours of dispensing, they crossed in longitude (calculated to be $\sim$ 17 km apart in altitude), increasing in longitude separation by $\sim$ 0.3°/day.

It was desired to station LES-9 east and LES-8 west of Lexington for the Joint Test Program, so thrusting operations had to be carried out to restore order and put LES-8 west of LES-9 again. The likelihood that the satellites would collide when re-crossing was vanishingly small, but the consequences of this improbable catastrophe would have been horrendous. Careful orbit-fitting was done as soon as preliminary equipment checkouts indicated that the K-band communications sub-systems had arrived safely in orbit. A thrusting strategy was selected and carried out on both satellites on 1976 March 16. They recrossed on 1976 March 19 with a minimum separation of $\sim$ 37 km (measured by sending ranging signals through the satellites).

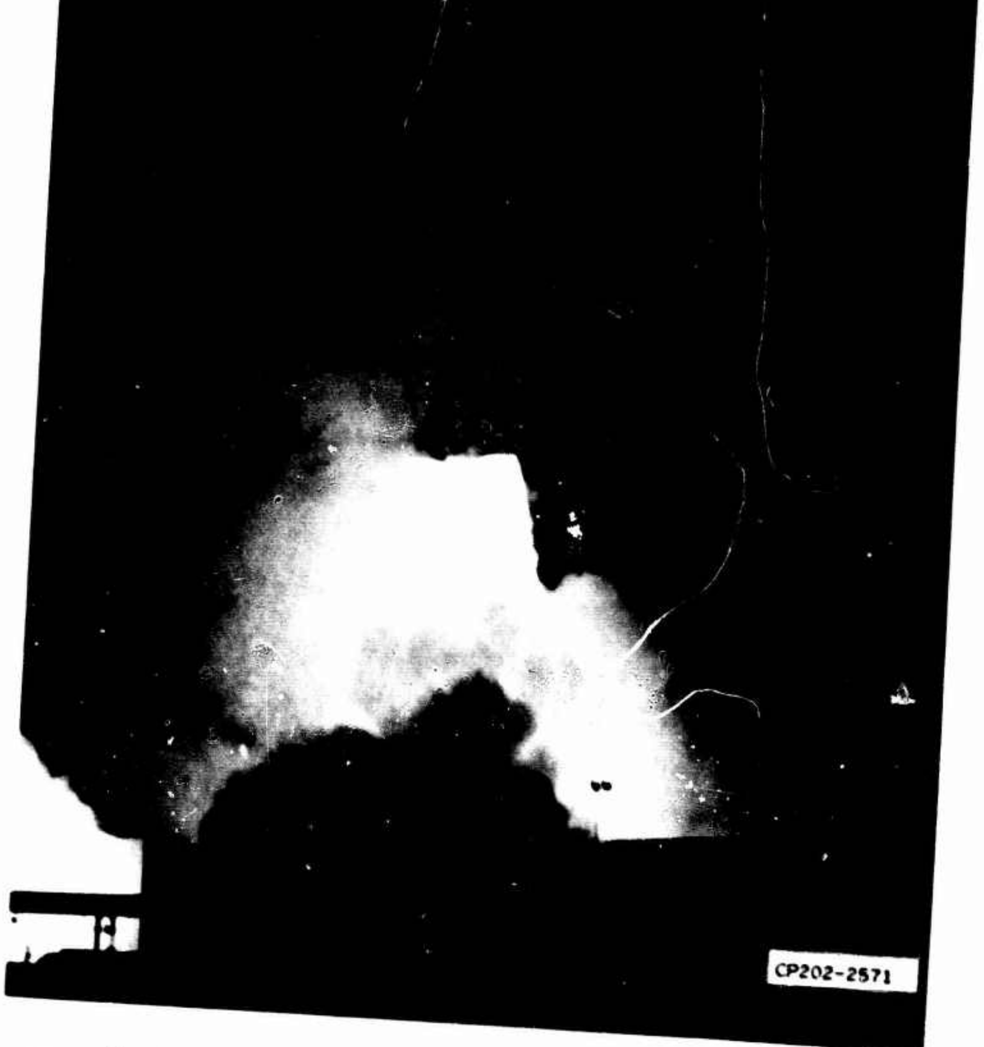

Fig. 16. The P76-1 Launch. Titan III-C booster C-30 (vehicle [illegible]) plus payload departing Launch Complex 40 at Cape Canaveral, Florida, on 14 March 1976 (Sunday) at approximately 2026 EST (15 March 1976 at approximately 0126 UTC).

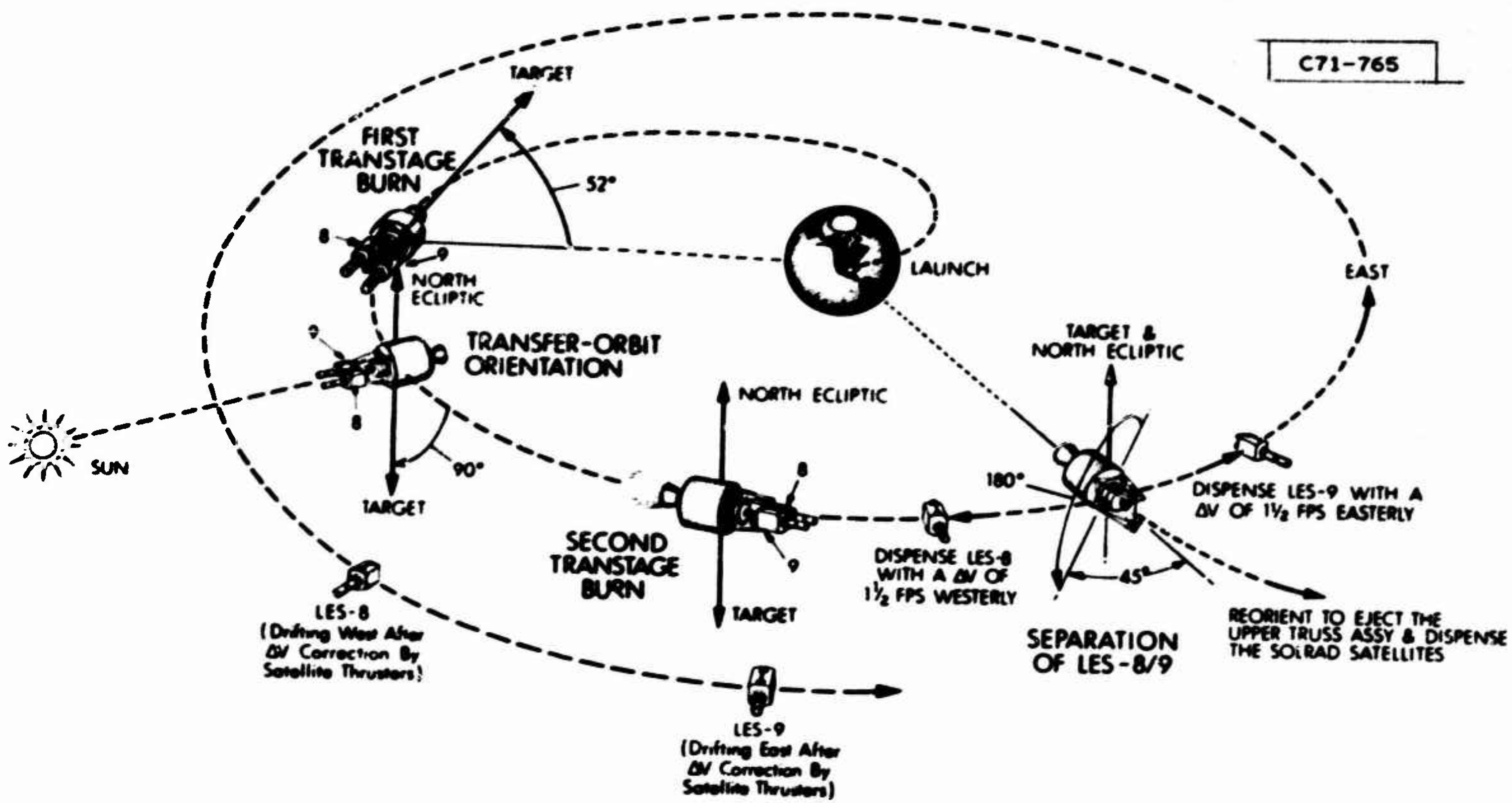

Fig. 17. Transfer orbit and separation procedure.

The longitude history of LES-8 is shown in Fig. 18. Soon after the interchange maneuver, LES-8 was thrusted to accelerate its drift westward. It was brought on station near 110°W under control of its autonomous stationkeeping system operating in the overdamped mode (Ref. 14). At the conclusion of this test period (1976 July 07 - October 04), LES-8 was allowed to drift east under the influence of the geopotential (Fig. 19). LES-8 has been thrusted about once a year since then to keep it in the general vicinity of its nominal station (110°W). There has been no need to control the daily-averaged sub-satellite longitude more closely than $\sim \pm 5°$. In the neighborhood of the stable equilibrium point of the geopotential (near 105°W for a satellite in circular, synchronous orbit with 25° equatorial inclination), the perturbing forces are very small, so thrusting need be only infrequent.

The longitude history of LES-9 is also shown in Fig. 18. It was thought at first that no additional thrusting would be required after the interchange maneuver, but tracking data soon showed that LES-9 would fail to reach 40°W before reversing course under the effect of the geopotential. So, LES-9 was thrusted again a few weeks after launch. It went somewhat east of 40°W and returned. In mid-1977 the LES-9 stationkeeping system was activated, to bring the satellite to 40°W in the underdamped mode and hold it there. This test was aborted after an undiagnosed on-board glitch in the stationkeeping system precipitated abnormal thrusting (on day 475 in Fig. 18). LES-9 was allowed to continue drifting east. Shortly after the conclusion of the Joint Test Program, LL was asked by DoD to reposition LES-9 near 95°W, for operational use by the Services. That transfer was made starting at $\sim 0.3°$/day and accelerating to $\sim 0.5°$/day under the influence of the geopotential. In conformity with the $\sim \pm 5°$ stationkeeping requirement, LES-9 was allowed to travel well west of 95°W before its westward drift was stopped and a slight eastward drift was established. LES-9 will be thrusted about once a year to hold station.

The sub-satellite tracks of LES-8/9 at their present nominal stations are shown in Fig. 20. The corresponding inter-satellite distance is

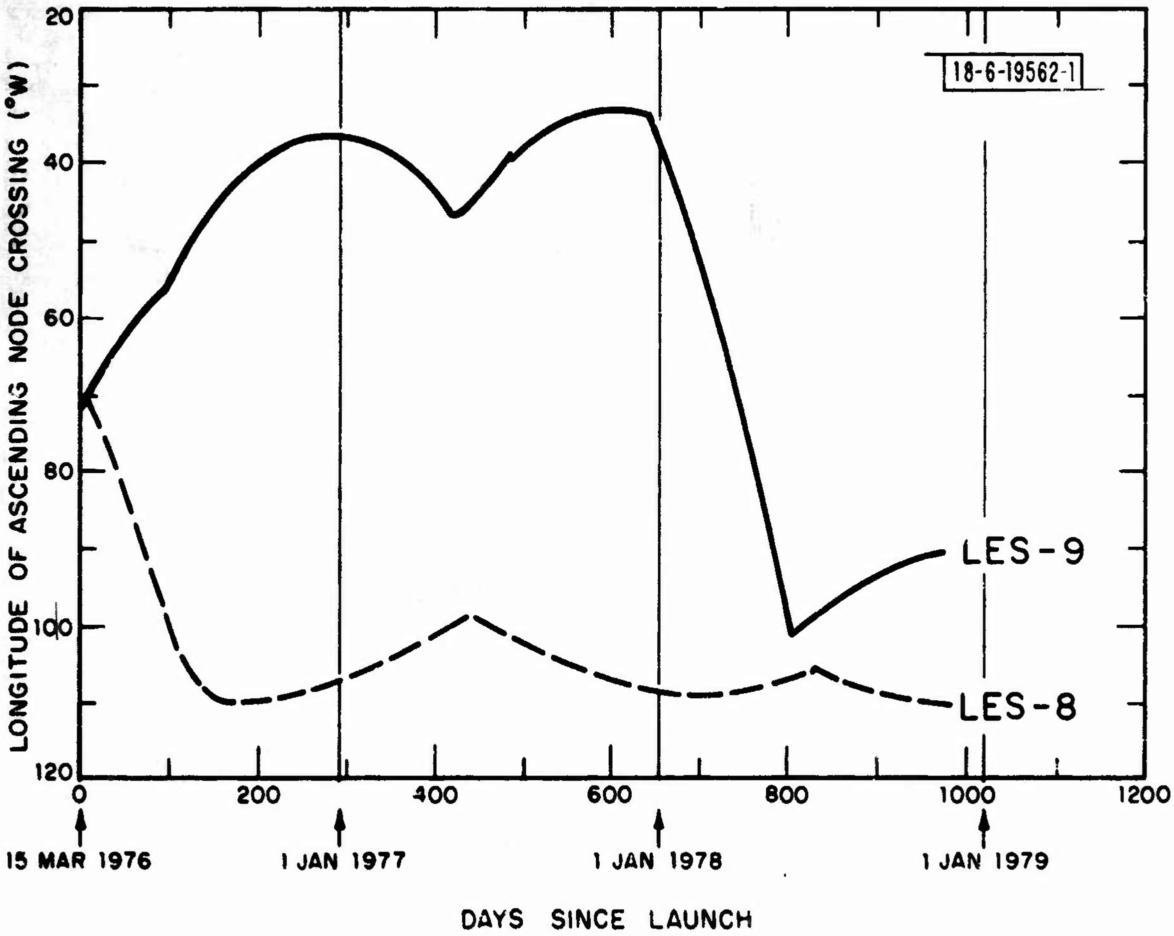

Fig. 18. Longitude histories of LES-8/9.

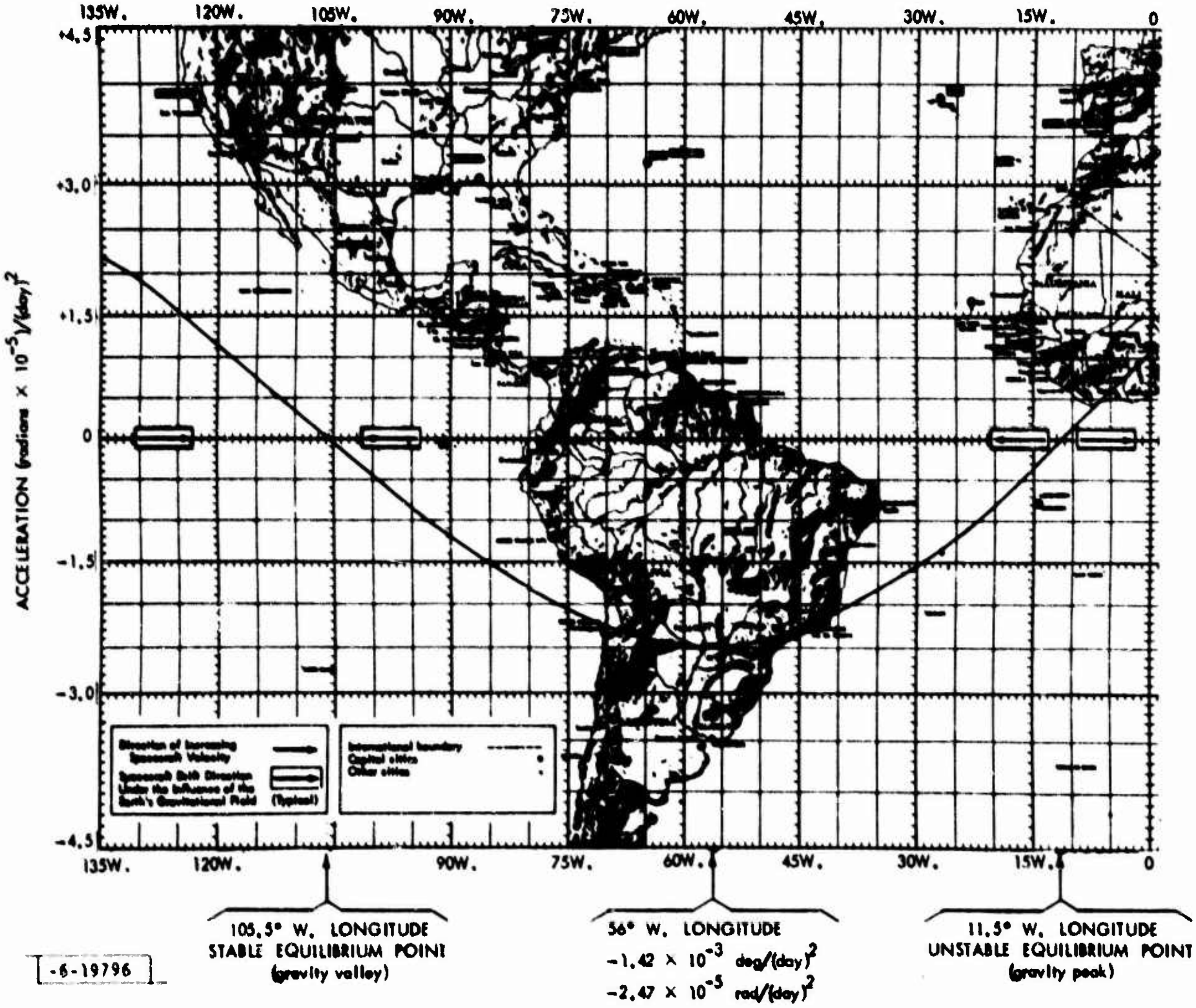

Fig. 19. Longitudinal drift acceleration vs longitude for a geostationary satellite. (Bullock & Wagner, NASA/GSFC, 1970, Ref.15.) For LES-8 and LES-9 in circular, synchronous orbits inclined 25° to the Earth's equator, the accelerations are about 8% smaller in absolute value (Ref. 16).

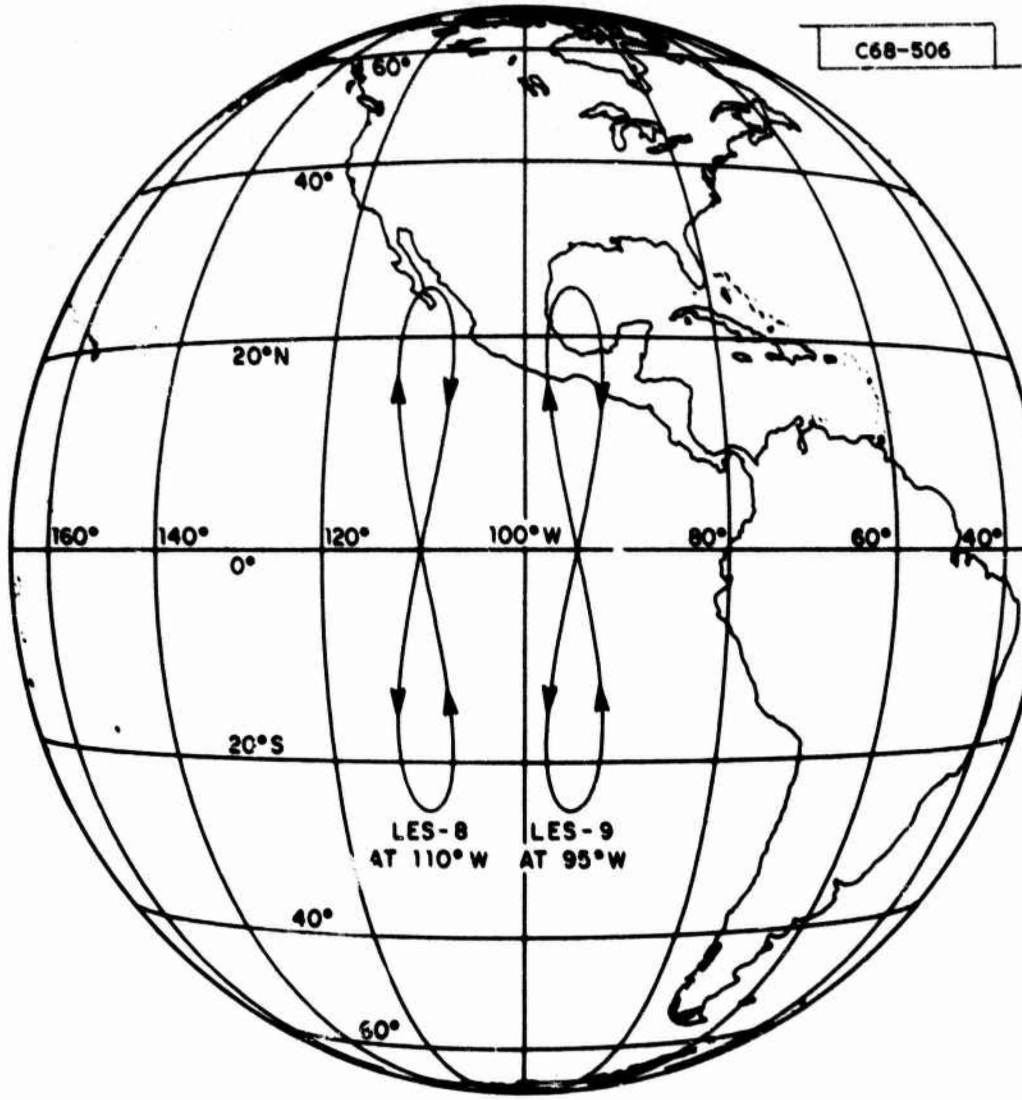

Fig. 20. Permanent stations for LES-8/9.

$2 \times 42,164.3 \sin[(110° - 95°)/2] \approx 11,000$ km. At their greatest separation in average sub-satellite longitude ($\sim 75°$, see Fig. 18), the satellites were $\approx 50,000$ km apart.

VIII. ORBIT DETERMINATION

Once LES-8/9 were in orbit, the Aerospace Defense Command commenced maintaining files of orbital elements on them, as with any other newly launched satellites. LES-8 and LES-9 are identified as Objects 8746 and 8747 respectively*. As soon as LES-8/9 had been dispensed by the Titan III-C Transtage, the Lincoln Laboratory Millstone Hill radar station commenced taking skin-track radar data to provide the first orbit-fits on the satellites (Ref. 17). As mentioned in Section VII, the K-band communications systems of LES-8/9 were employed in a repeater mode for collection of ranging data which were used (together with azimuth and elevation-angle data from the tracking LL ABNCP terminal) to determine the two sets of orbital elements on which the initial thrusting strategy was based.

LL sought to obtain ultra-precise "before" and "after" orbit-fits on LES-8/9 for careful evaluation of thruster effectiveness in GPSS operation, for example. There was also a requirement to provide good orbital elements to the K-band communications terminals, ABNCP (Ref. 18) and Navy (Ref. 19). Both LL and Service K-band terminals needed this information. That need was met through use of the Planetary Ephemeris Program (PEP, Ref. 20). This awesome wonder (the version now in use at LL corresponds to $\sim$ 90,000 cards) was originally developed to support a Fourth Test of Einstein's General Theory of Relativity (Ref. 21, 22). PEP has subsequently been used in processing data collected from NASA interplanetary space probes. In the LES-8/9 application, PEP accepts coherent-Doppler-shift data (proportional to range rate) as well as the usual range data and the two pointing angles. The signal-processing circuitry in the LES-8/9 communications system allows either mode to be operated (range or coherent Doppler). They are time-shared by command during a data-taking period.

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*LES-8 and LES-9 have also been designated 1976-23A and 1976-23B respectively.

This application of PEP has been highly satisfactory. There were bugs to be gotten out of the hardware and the software, of course. We were unable to devise a way to test the whole system until these particular satellites were in orbit. As the enterprise was perfected, we found that it was possible to predict the motion of LES-8/9 under the influence of the Earth's geopotential quite well. The occasional thrusting operations on the satellites (Fig. 18) were tailored to produce the ensuing orbital excursions. The sizable community of customers for LES-8/9 orbital elements and antenna-pointing predictions has been well-served.

IX. CHOICE OF ORBITS

The choice of orbits for LES-8/9 (and the P74-1 mission) can always be counted on to raise questions. Why were LES-8/9 placed in coplanar circular, synchronous orbits inclined $\sim 25°$ to the Earth's equatorial plane (near-ecliptic)? Communications satellites have generally been placed either in geostationary orbits (circular, synchronous, near-equatorial) or in Molniya-like orbits (eccentricity ≈ 0.74, half-synchronous period, $\sim 63°$ equatorial inclination). The fundamental answer is that, early in the program, the payloads (LES-8/9 and NRL's SOLRAD-11 A/B Sun-monitoring satellites) were expected to be rather heavy. Given the finite performance of the Titan III-C booster, a more massive payload could be launched if little or no plane-changing was required when circularizing to synchronous orbit at the apogee of the transfer ellipse. It was possible, by study and compromise, to meet the separate orbital requirements of the higher-altitude SOLRAD-11A/B satellites as well. The orbital plane of LES-8/9 was judiciously chosen near the ecliptic plane, a posture that is advantageous, incidentally, for evaluating the performance of the third-generation-gyro systems (built by the Charles Stark Draper Laboratory) carried by LES-8/9. The low-drift-rate performance of the third-generation-gyro system can be ascertained from the time series of the instants (once a day) when a special Sun-transit sensor (integral with the gyro package) is triggered.

The orbital planes of LES-8/9 may never actually lie in the ecliptic plane. The initial ecliptic inclination (5.7°) decreases to about 2° three years after launch and then increases to about 5° five years after launch. The particular choice of initial orbital elements for LES-8/9 was a compromise between (a) keeping LES-8/9 as close to the ecliptic plane as possible during the initial five years in orbit (when tests and experiments are most likely to be conducted) and (b) having the smallest possible plane change from the parking orbit (28.6° equatorial inclination), to obtain the largest possible payload mass capability.

The ecliptic inclination of the LES-8/9 orbital planes will continue to grow slowly after five years in orbit. This effect (which is primarily caused by the Earth's equatorial bulge, but which has a component due to the lunar and solar masses) has a full period of about 80 years. Under simplifying assumptions, the ecliptic inclination might approach 50° some 40 years after launch, then return nearly to zero after another 40 years, and so on. The verification of this prediction must be left to others.

Working with a satellite such as LES-8 or LES-9 presents some unusual operating problems. A terminal that must track it in angle sees large antenna motion during a day of service. During the Joint Test Program, LES-8/9 were kept sufficiently close to the longitude of Lexington so that they never "set" below the local horizon of the control facilities. Figure 21 shows that, for $\sim$ 5° minimum elevation angle at Lexington, LES-8 should not be allowed to go much west of 109°W, LES-9 much east of 34°W. 5° provides a little margin above the $\sim$ 3° limit set by local terrain. 5° is enough elevation angle to provide usable UHF and S-band propagation in most circumstances, although K-band is often unreliable at that low an angle. Of course, the satellite does not spend all its time down there. When critical K-band work had to be done from Lexington (taking data for orbit-fitting, for example), it was scheduled for a time when the satellite had a high elevation angle. As Fig. 22 suggests, this was sometimes at an awkward hour A satellite that reaches its northernmost excursion (with consequent good viewing from Lexington) in the middle of

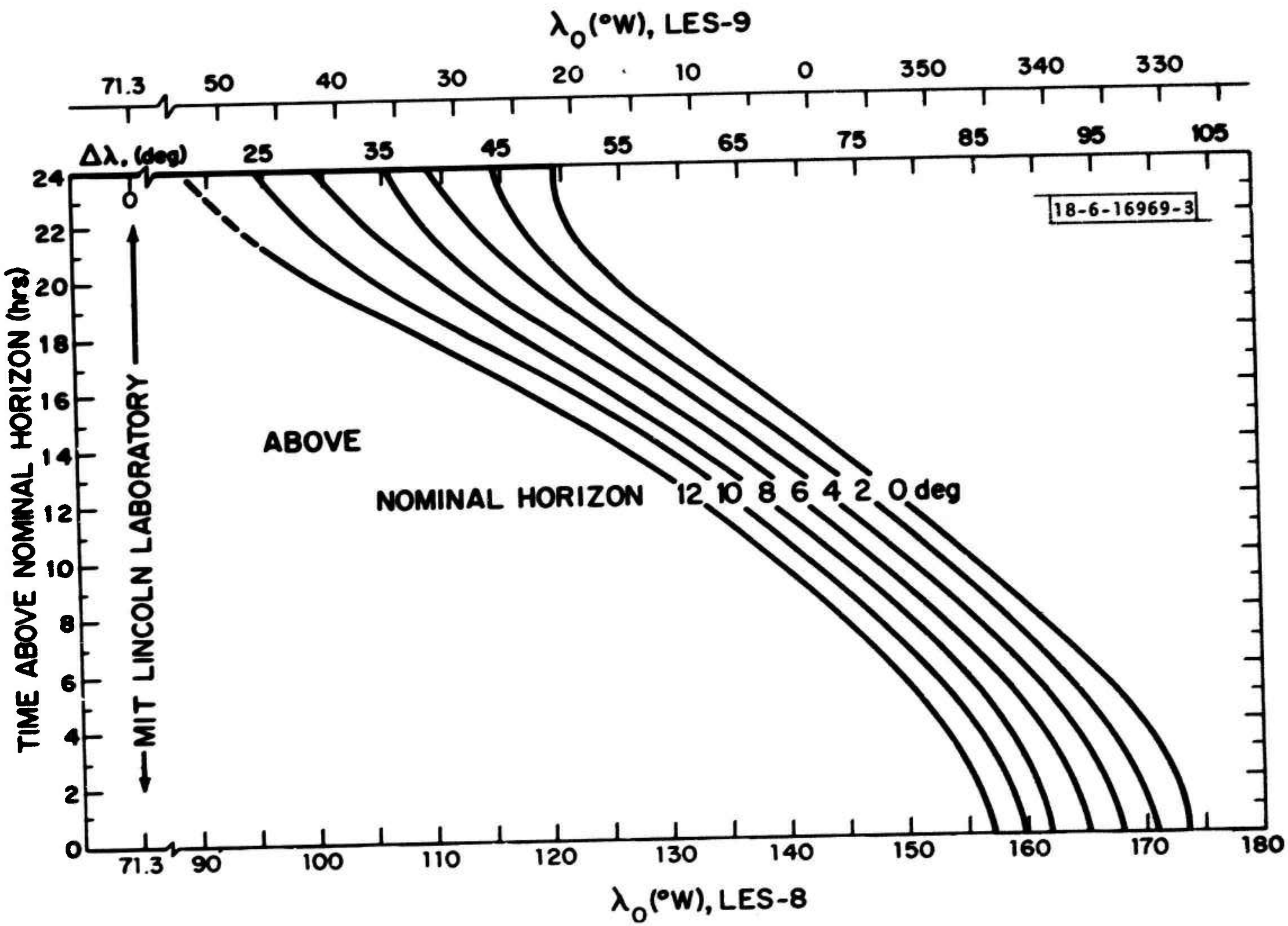


Fig. 21. LES-8/9 visibility from Lexington, Massachusetts.

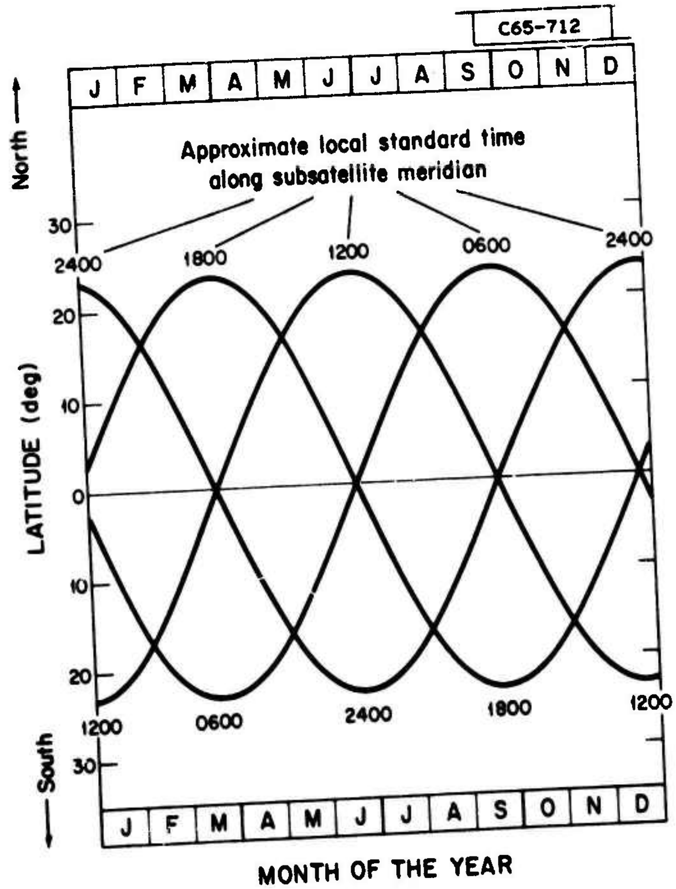


Fig. 22. Subsatellite latitude (circular, synchronous, ecliptic-plane orbit).

normal working hours at one season would, 6 months later, be in that useful position 12 hours earlier, in the middle of the night.

Putting LES-8/9 into near-ecliptic orbital planes resulted in having each satellite eclipsed by the Earth for ∿ 70 min every day. Geostationary satellites are eclipsed by the Earth during two ∿ two-month-long seasons each year (centered on the equinoxes). Those eclipses increase from zero duration to ∿ 70 min and then decrease back to zero. LES-8/9 have therefore already experienced thermal cycling during eclipses corresponding to a great many years of service for a geostationary satellite. Thanks to the RTGs, LES-8/9 remain fully functional during eclipse, with no necessity to switch power loads between the power source and the battery system or to charge up the battery system between eclipses.

The ± 25° daily latitude excursions of LES-8/9 yield intervals of polar coverage not afforded by geostationary satellites, allowing communications-link tests to be made with terminals in the polar environment. It can be argued that LES-8/9 do not contribute significantly to congestion in the geostationary-orbit corridor (particularly in the neighborhood of the stable point of geopotential, Fig. 19), for they spend only a small fraction of each orbital period near the equator. The substantially inclined orbits of LES-8/9 provide a good challenge to sophisticated terminals (such as the K-band ABNCP terminals). The K-band frequency-hopped 8-ary-MFSK uplink signals must be precorrected in timing (for changing slant range) and in frequency (for changing Doppler shift) so that these transmissions arrive at LES-8 or LES-9 in accurate synchronism with the counterpart functional operations of the uplink receiver.* The inclined orbits of LES-8/9 are more sporting. They offer their own distinctive benefits.

*The UHF uplink portion of the LES-8/9 communications system has been designed so that the less-sophisticated UHF force-element terminals can have access to the satellites under less-stringent conditions.

X. JOINT TEST PROGRAM

The LES-8/9 Joint Test Program, managed by the Electronic Systems Division (ESD), Air Force Systems Command (AFSC), involved not only the satellites and the communications terminals built by LL, but also terminals developed by the Services. The testing included multi-faceted operation of terminals and special test facilities at field sites, in aircraft, and at sea (Fig. 23).

LL's post-launch communcations-system testing was divided into 4 phases:

I	Initial operations - initial orbital operations sub-system checks link-verification checks
II	Quantitative satellite communications-subsystem tests
III	Detailed link measurements and demonstrations by LL
IV	Cooperative link demonstrations and measurements with Service terminals.

Phase I occupied the first 2 weeks after launch. Phase II took the next 9 weeks. There was no sharp division between Phases III and IV, but rather considerable overlap. For all practical purposes, Phase III (which started at the beginning of 1976 June) was completed by 1976 Fall, Phase IV by 1977 Summer. A few individual tests were not accomplished until later. Technical testing and military-utility demonstrations by the Services commenced as satellite time began to be available to them in Phase II. The Joint Test Program was officially and successfully concluded at the end of 1977 September, several months ahead of schedule. However, the inventive intellects of the testing community have brought forward some more interesting things to try. Technical testing continues at a low level in the satellites' present operational-capability phase, LES-8 being the principal resource for that purpose. LL has published the major results of its communications-link testing (Ref. 12).

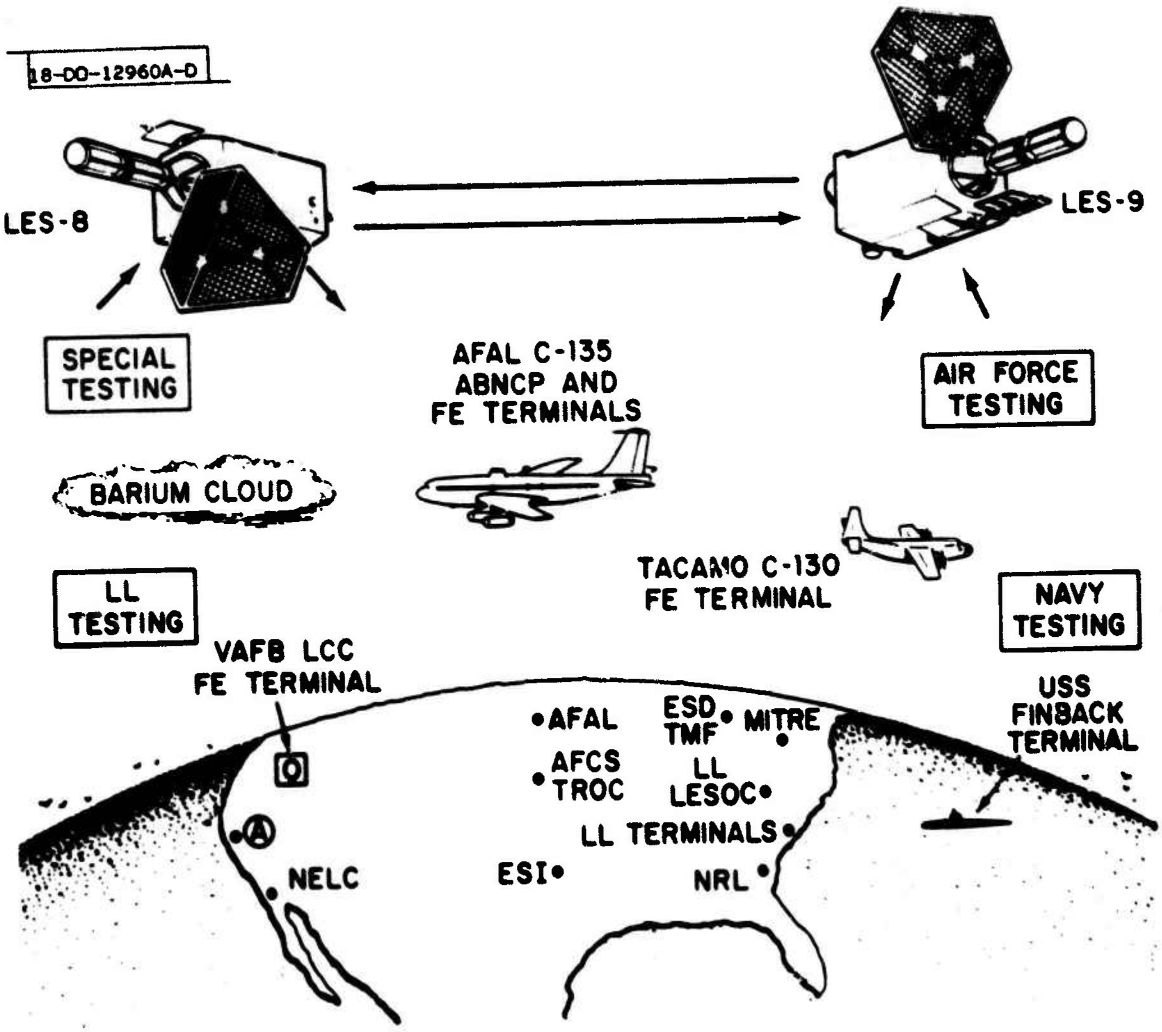


Fig. 23. LES-8/9 communications-system testing in orbit.

XI. LESOC

The management of LES-8/9 in orbit has been carried out almost entirely from Lincoln Laboratory facilities in Lexington, Mass. Figures 24 and 25 show the present control arrangements. During the formal LES-8/9 Joint Test Program, the scheduling and coordination functions now carried out by the Air Force Communications Service (AFCS) and its Tactical Relay Operations Center (TROC) were handled from the Test-Management Facility (TMF) at ESD, connected to LESOC by two-way data links for exchange of extensive satellite command and telemetry information.

LESOC was developed in large part by the same engineers, technicians, and programmers who developed and tested the satellites themselves. This continuity of experience was invaluable. A person who had nursed a spacecraft subsystem through its formative phases and readied it for integration, system testing, and launch-ready delivery knew (better than anyone else could know) which items of information would be most helpful in handling possible post-launch problems. The LESOC challenge lay in devising good ways to present this critical information.

What resulted (in terms of data displays and operating consoles) is multi-faceted and self-complementary. The main computer complex in LESOC does wholesale processing of detected telemetry data from both satellites simultaneously. Among other things, for each satellite the main computer complex records the incoming data (all of it for low-rate operation, all or part of it for high-rate operation), monitors sets of telemetry points for out-of-tolerance data indicating actual or incipient trouble (sounding an alarm when called for), and generates a large number of page and half-page CRT displays of system and subsystem performance. The CRT displays are updated in real time as incoming telemetry data is processed in the main computer complex.

For example, Fig. 26 shows a balance-sheet display of power-system status (PWRST) for LES-8. The currents and the bus voltage of the two paralleled RTGs are measured, making possible an approximate calculation of the power at the

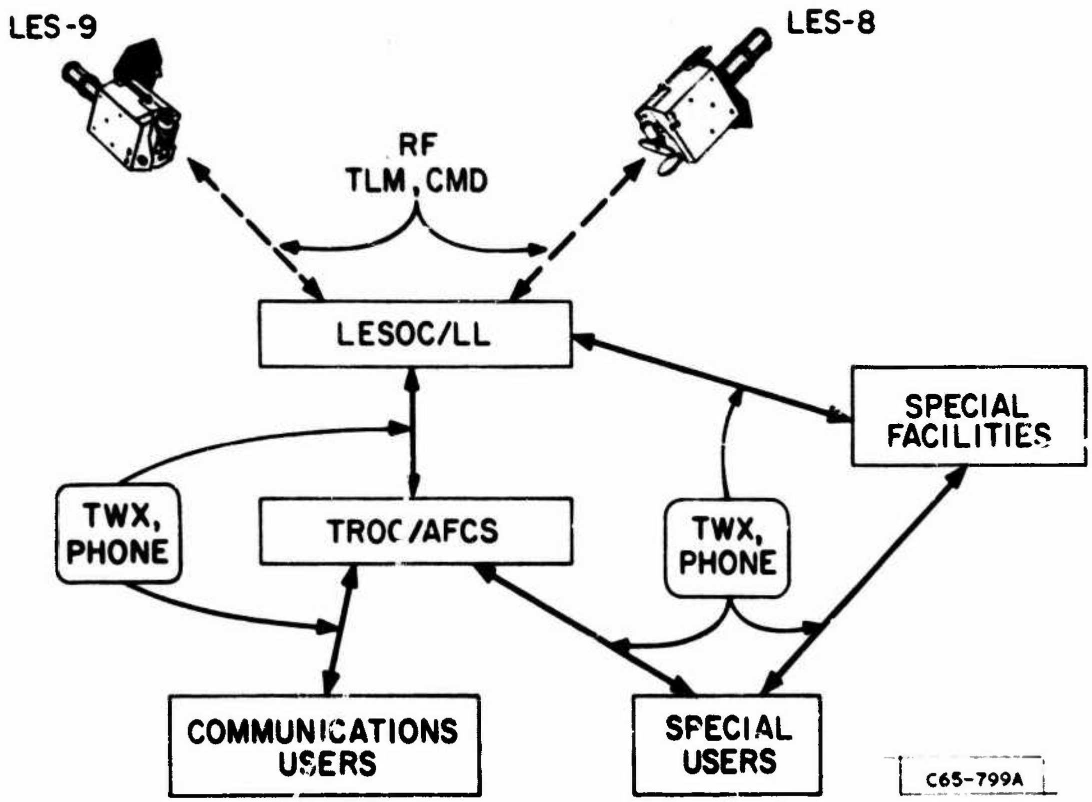


Fig. 24. Control flow for LES-8/9.

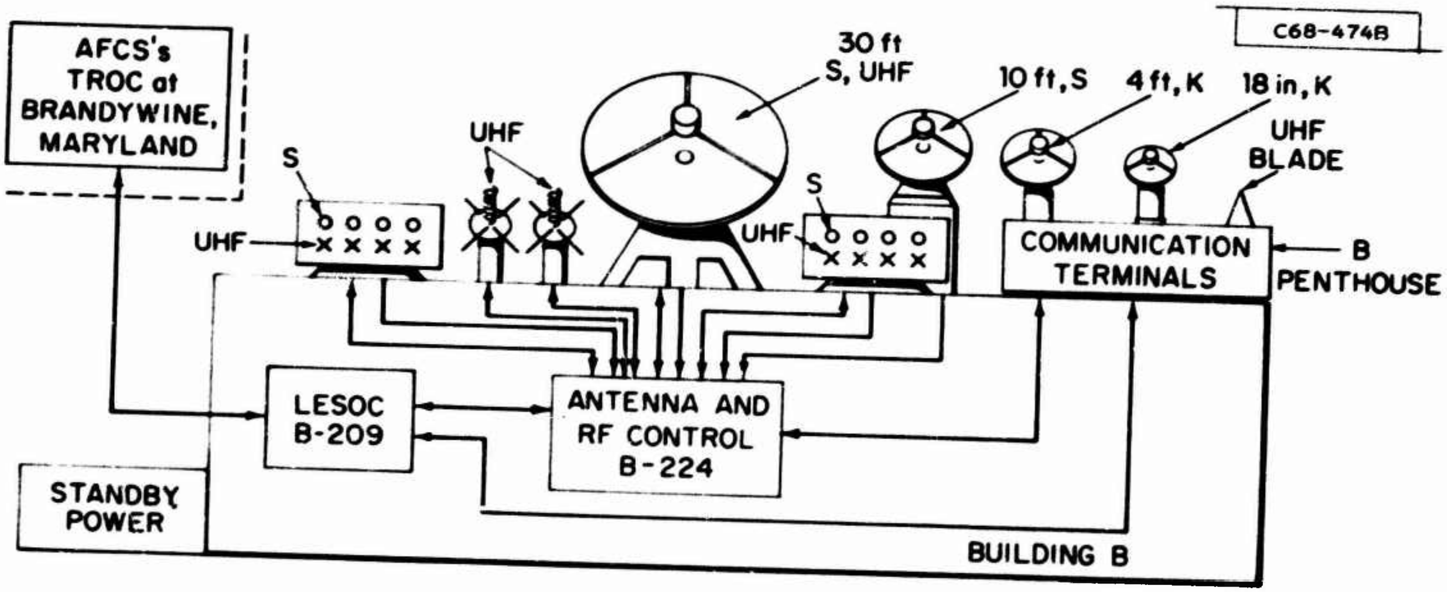
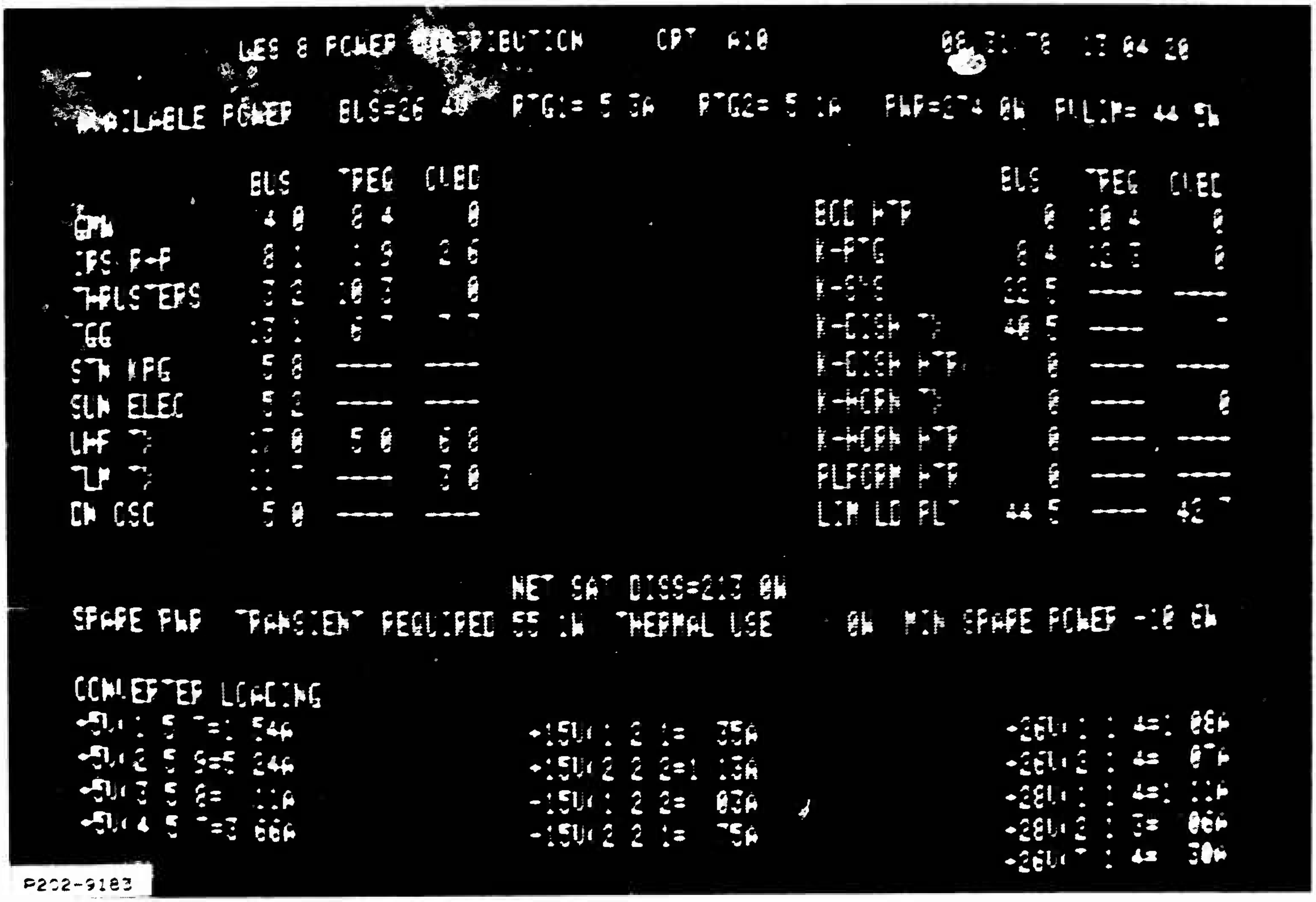


Fig. 25. LES-8/9 ground-station facilities at Lincoln Laboratory, Lexington, Massachusetts.



LES 8 POWER DISTRIBUTION OPT A10 08 31 78 13 04 28

AVAILABLE POWER BUS=26 [illegible] RTG1= 5 3A RTG2= 5 1A PWR=274 0W PULIM= 44 5W

	BUS	TREG	OVED
CPU	4 0	8 4	0
IRS R-R	8 1	1 9	2 6
THRUSTERS	3 2	10 3	0
TGG	13 1	6 [illegible]	[illegible]
STW KPG	5 8	----	----
SUN ELEC	5 2	----	----
UHF TX	17 0	5 0	6 8
TLM TX	11 [illegible]	----	3 0
CN OSC	5 0	----	----

	BUS	TREG	OVED
ECD HTR	0	10 4	0
K-RTG	6 4	10 3	0
K-SYS	22 5	----	----
K-DISH TX	46 5	----	-
K-DISH HTR	0	----	----
K-HORN TX	0	----	0
K-HORN HTR	0	----	----
PLFORM HTR	0	----	----
LIM LD PLT	44 5	----	42 [illegible]

NET SAT DISS=213 0W

SPARE PWR TRANSIENT REQUIRED 55 1W THERMAL USE 0W MIN SPARE POWER -10 6W

CONVERTER LOADING

+5V(1 5 [illegible]=1 54A	+15V(1 2 1= 35A	+26V(1 1 4=1 08A
+5V(2 5 9=5 24A	+15V(2 2 2=1 13A	+26V(2 1 4= 07A
+5V(3 5 8= 11A	-15V(1 2 2= 03A	+28V(1 1 4=1 11A
+5V(4 5 [illegible]=3 66A	-15V(2 2 1= 75A	+28V(2 1 3= 06A
		+26V([illegible] 1 4= 30A

P202-9183

bus (the instrument-quality telemetry gives more significant figures than shown in Fig. 26, but the three measurements are not made simultaneously). The bus loads corresponding to the numerous ON/OFF systems and sub-systems are tabulated as line-item entries for bus power. The critical number in Fig. 26 corresponds to the power being dumped overboard in the voltage limiter (PVLIM, upper right-hand corner). That number must remain large enough so that there is always a prudent reserve of power for operation of autonomous on-board functions (actuation of thruster valves when dumping solar-radiation-pressure-imparted angular momentum, for example). Failure to keep enough reserve power in the bank can result in dropping the bus voltage far out of regulation, at which point the load-shedding thresholds in the power system would call for automatic shut-OFF of various spacecraft sub-systems. Any decision to turn something ON must be made with awareness of how much power margin is available above this reserve. As the years go by and less power is available from the RTGs (Section XIII), such decisions must be made with increasing care. The negative number displayed for minimum spare power in Fig. 26 does not indicate that the satellite was in a risky situation. Rather, the algorithm for computing minimum spare power is excessively conservative.

The page and half-page displays can present -- in principle -- all the information that is available in the telemetry data streams, to any desired precision. However, they do a poor job of presenting the relationships among the various items of information. To get around that problem, displays were developed for LESOC to present telemetry information on the housekeeping systems in block-diagram/flow-chart form. Figure 27, showing the display for the LES-8 gimbaled-momentum-wheel control system (GMWCS), is an example. It can be seen that the TGGS was controlling the satellite in pitch. The roll IRS was controlling it in roll. The wheel was running near the top of its speed range. The errors in pitch and roll were small. No thrusting was being called for by the autonomous GMWCS. The temperature and motor power of the GMW itself were normal. Displays of this sort, depicting the system configuration in crystal-clear form and presenting the present values of key variables in engineering units, are extremely helpful when troubleshooting incidents of

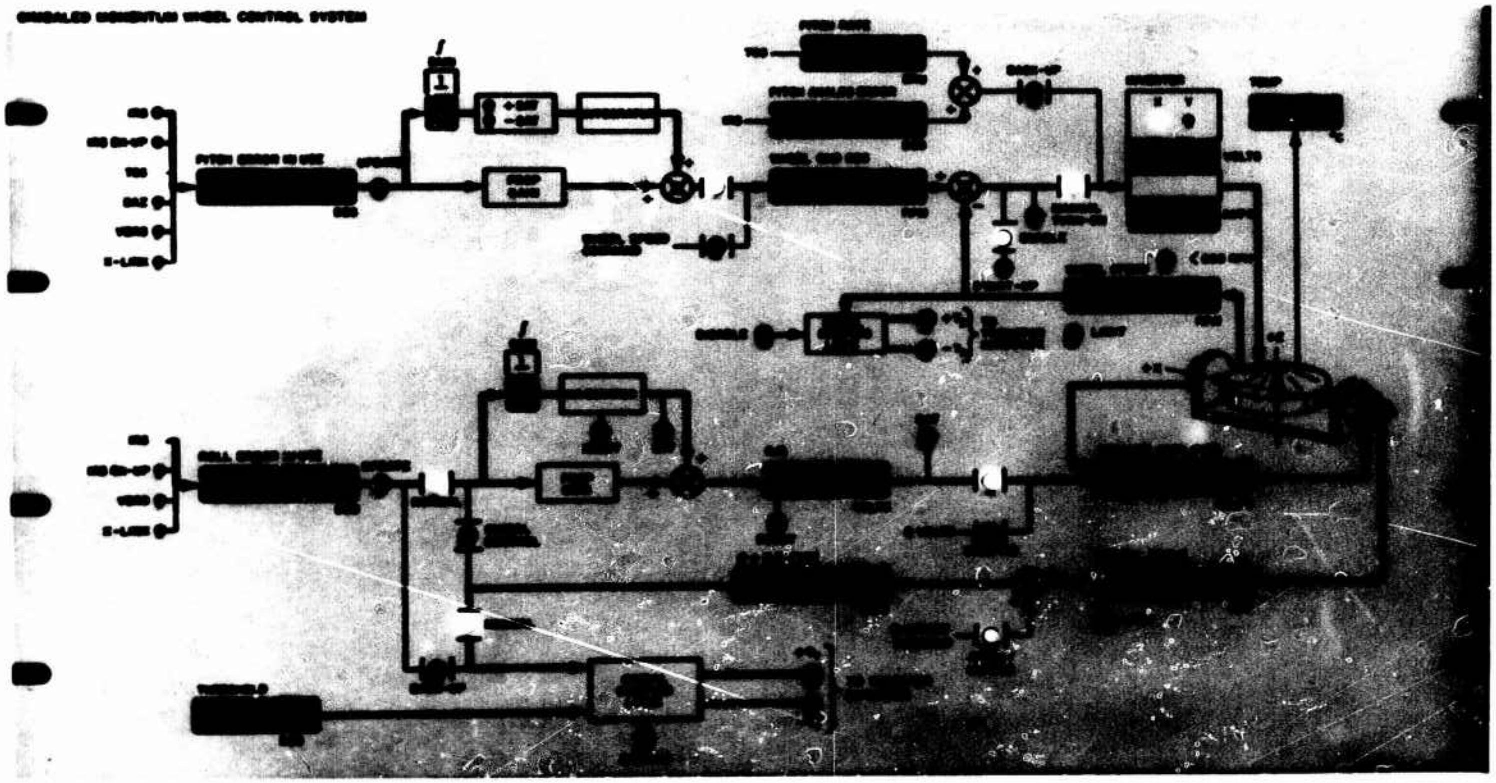


Fig. 27. Status-panel display for LES-8 GMWCS.

apparent satellite misbehavior. It has been our experience in LESOC that most of the problems arise from cockpit errors. The satellites are seldom at fault.

These housekeeping-system status panels display telemetry data that has been reduced by microprocessors that are part of the display electronics. If the main computer complex crashes and the CRT displays described above disappear, these status panels keep going, and vice versa.

Housekeeping-system commands (controlling functions such as those described above) are sent to LES-8/9 infrequently, so it is acceptable to set them up using a keyboard before verification and transmission. By contrast, communications-system commands may need to be sent rapidly and often. To accommodate that brisk workload, the communications-system status panels (Fig. 28) incorporate pushbuttons that can initiate the desired commands directly. Suppose it is desired to change the uplink receiver from K-band to UHF. All that is needed (given the keys to the protective interlocks, etc.) is to press the ARM button and the button corresponding to the desired switch position. The particular command bit sequence is called up from a read-only memory (ROM) and fed to the RF transmission facilities. After the command has been received by the satellite and acted on, telemetry data processed by the status-panel electronics (microprocessor plus discrete logic) will show [by light-emitting diodes (LEDs) OFF and ON] that the switch-throwing has taken place. It is possible to reconfigure the communications system rapidly and effectively by this technique, using relatively inexperienced help. Ref. 25 describes the communications-system status panels in greater detail, along with the status panels and system features of the intersatellite crosslink.

A communications-system status panel similar to Fig. 28 was installed in a C-135 airplane operated by the Air Force Avionics Laboratory (AFAL). The panel was an adjunct to the AFAL-developed K-band airborne-command-post (ABNCP) terminal. The LES-8/9 signal format made telemetry data (multiplexed with the downlink message data) available in the airplane. It was also possible to transmit commands using the uplink message format. The AFAL test team was thus prepared to control a satellite's communications system from the airplane, and

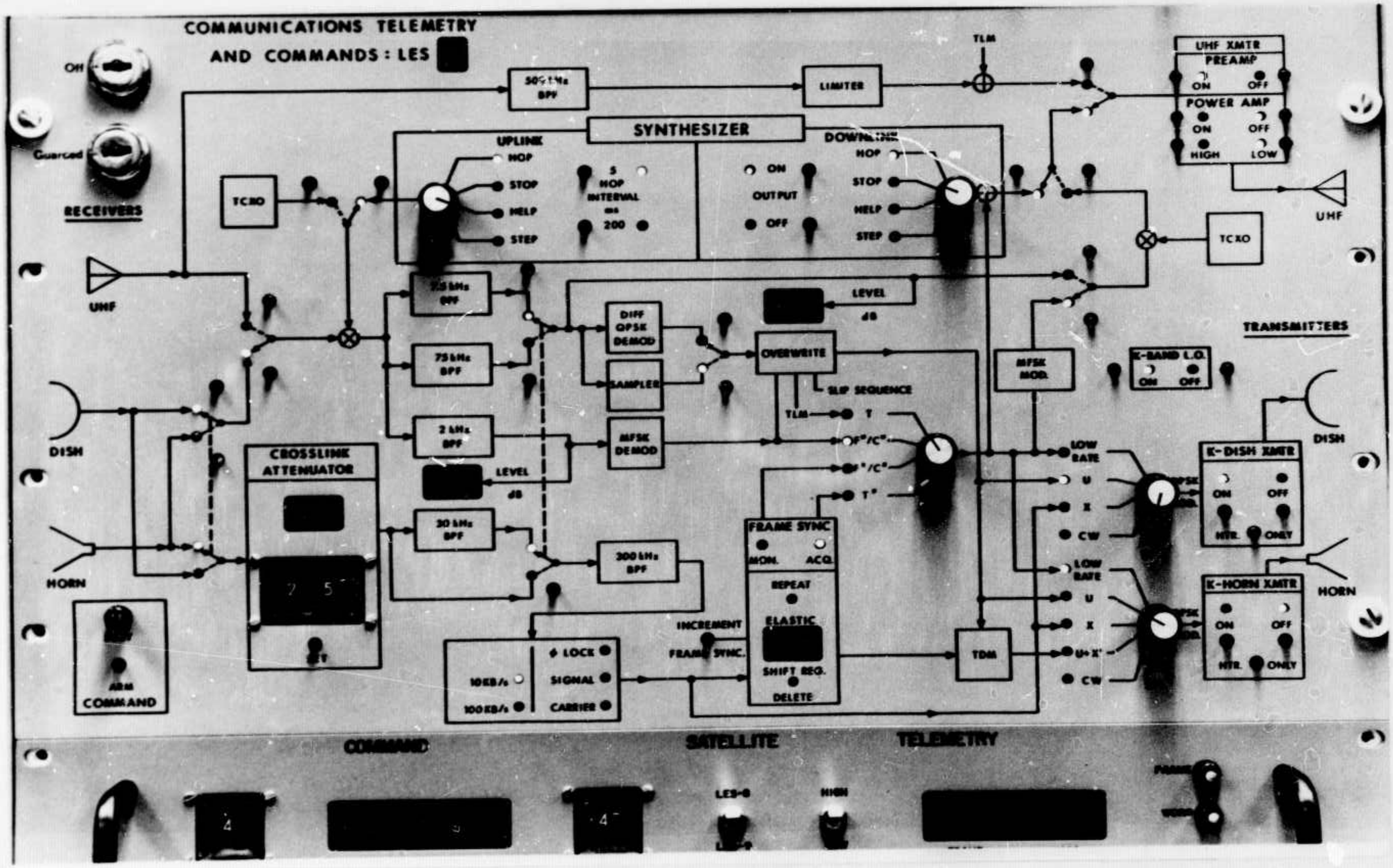


Fig. 28. Status-panel display for LES-8 communications system.

they have done so quite effectively during several flight-test series (Ref. 24). Although the airborne installation did not include status panels and control arrangements for a satellite's housekeeping systems, it would have been a straightforward task to have provided them. Managing a satellite in orbit does not necessarily require having a big ground-based Mission Control Center. The job can be done quite well using much simpler facilities.

In time, the availability of improved graphics terminals for computers should make it possible to generate displays (CRT, plasma panel, or whatever) that are the equals of the status panels for the LES-8/9 housekeeping and communications systems. Command initiation using a light pen, for example, would provide the essential interactive flexibility. It is also desirable to include in the panel's logic (which may be the software of the underlying computer) protective algorithms to lead the operator by the hand through a command sequence when there is any element of potential risk to the satellite. "Interlocking" features of this sort are already available at some installations.

Another class of LESOC displays is represented by Fig. 29. Telemetry data are processed by a minicomputer which also does the calculations involving the geometry of the orbit. This example shows that LES-9's K-band dish antenna is pointed so as to illuminate Lincoln Laboratory. The sub-satellite latitude and longitude are computed from orbital data stored on an ephemeris tape. The mount angles (AZ and EL) required to point LES-9's K-band dish antenna toward LES-8 are also given and can readily be transferred by command to holding registers in the satellite. Also provided are the angle offsets of the entire spacecraft body (pitch and roll) to improve the coverage by the fixed K-band horn antenna for either of two particular terminal sites.

Figures 30 through 34 present several interior views of LESOC, which is devoted almost entirely to LES-8/9 operations (there are occasional tasks associated with the maintenance of LES-6, which has been in reserve status since the launch of the first Gapfiller/Marisat satellite in 1976 March). A system of closed-circuit-television cameras and monitors and a separate

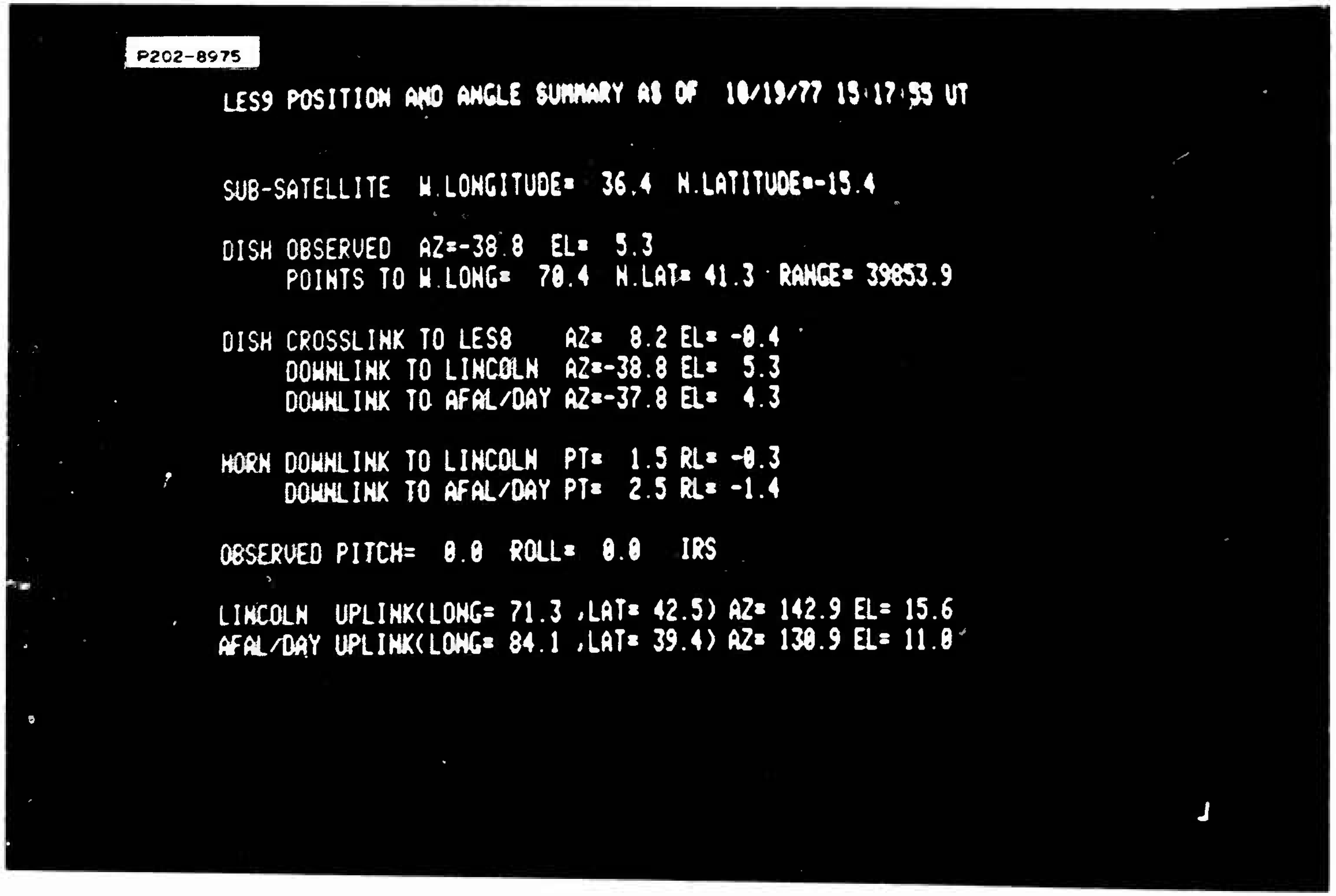


Fig. 29. CRT display of LES-9 position and angle data.

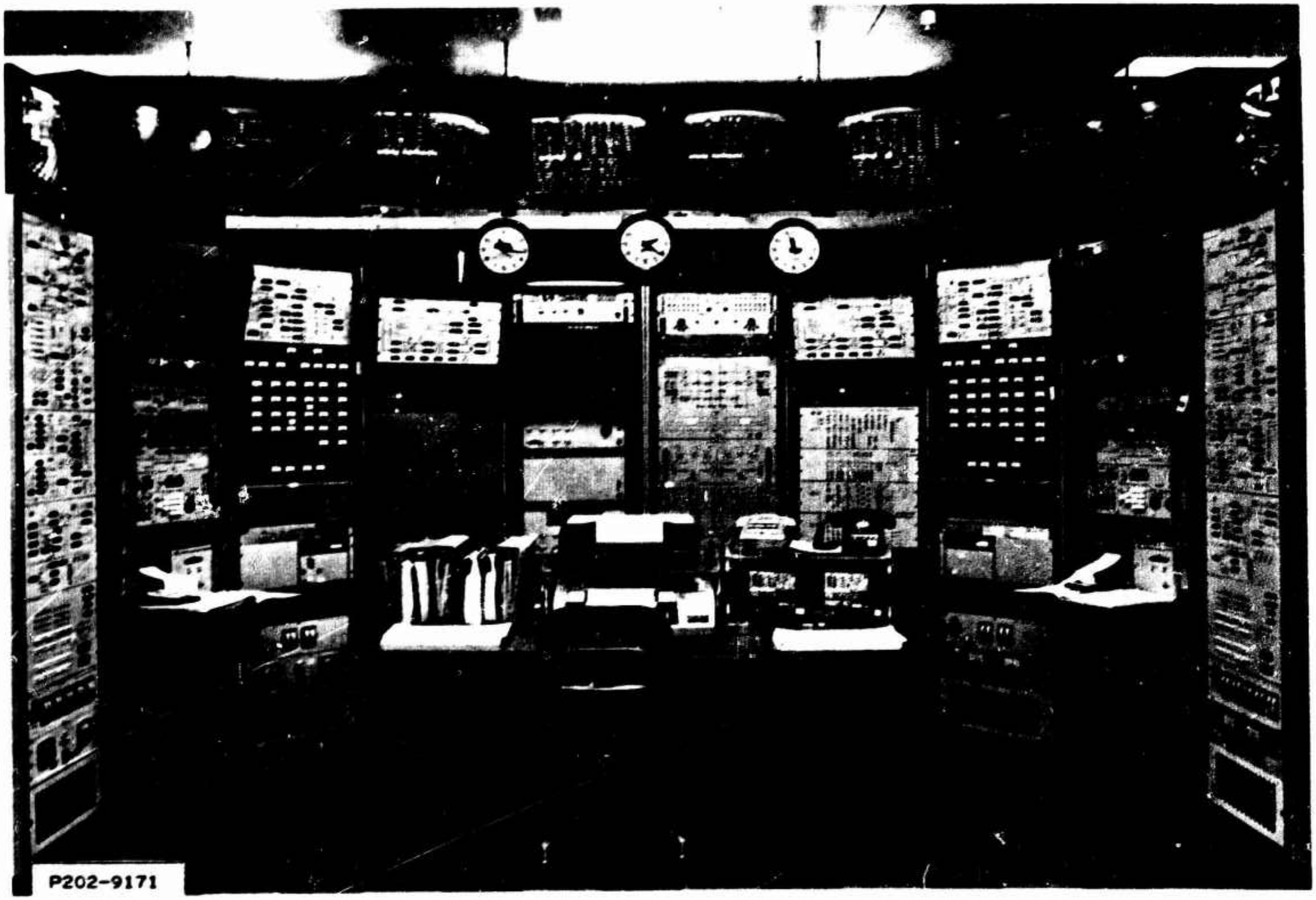


Fig. 30. Status and control panels in LESOC for the housekeeping systems of LES-8 (left) and LES-9 (right). A panel shown in Fig. 27 is at the top of each outermost rack. Ground-station command and telemetry facilities are managed from the panels in the center.

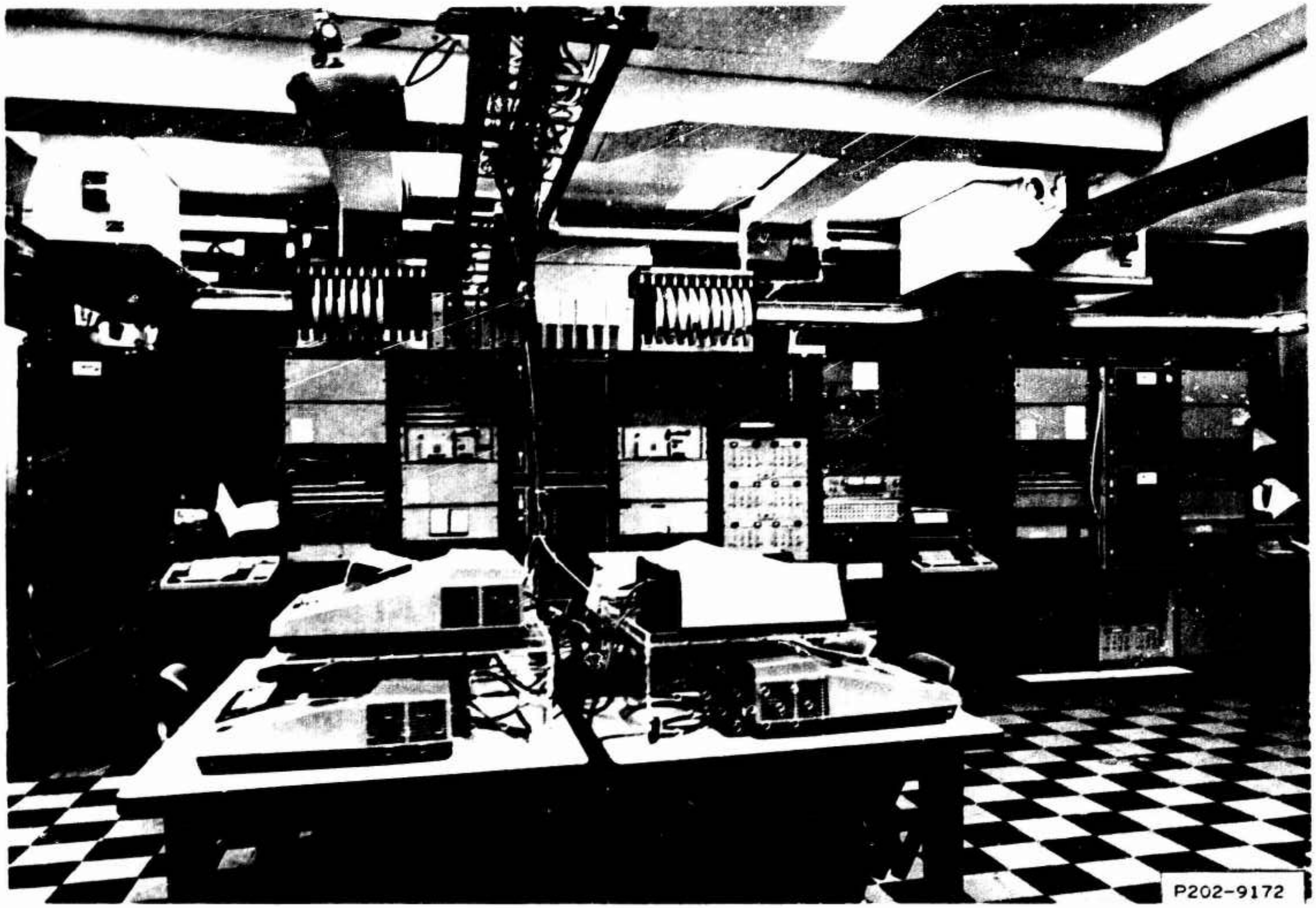


Fig. 31. General view of LESOC computer facility and peripherals.

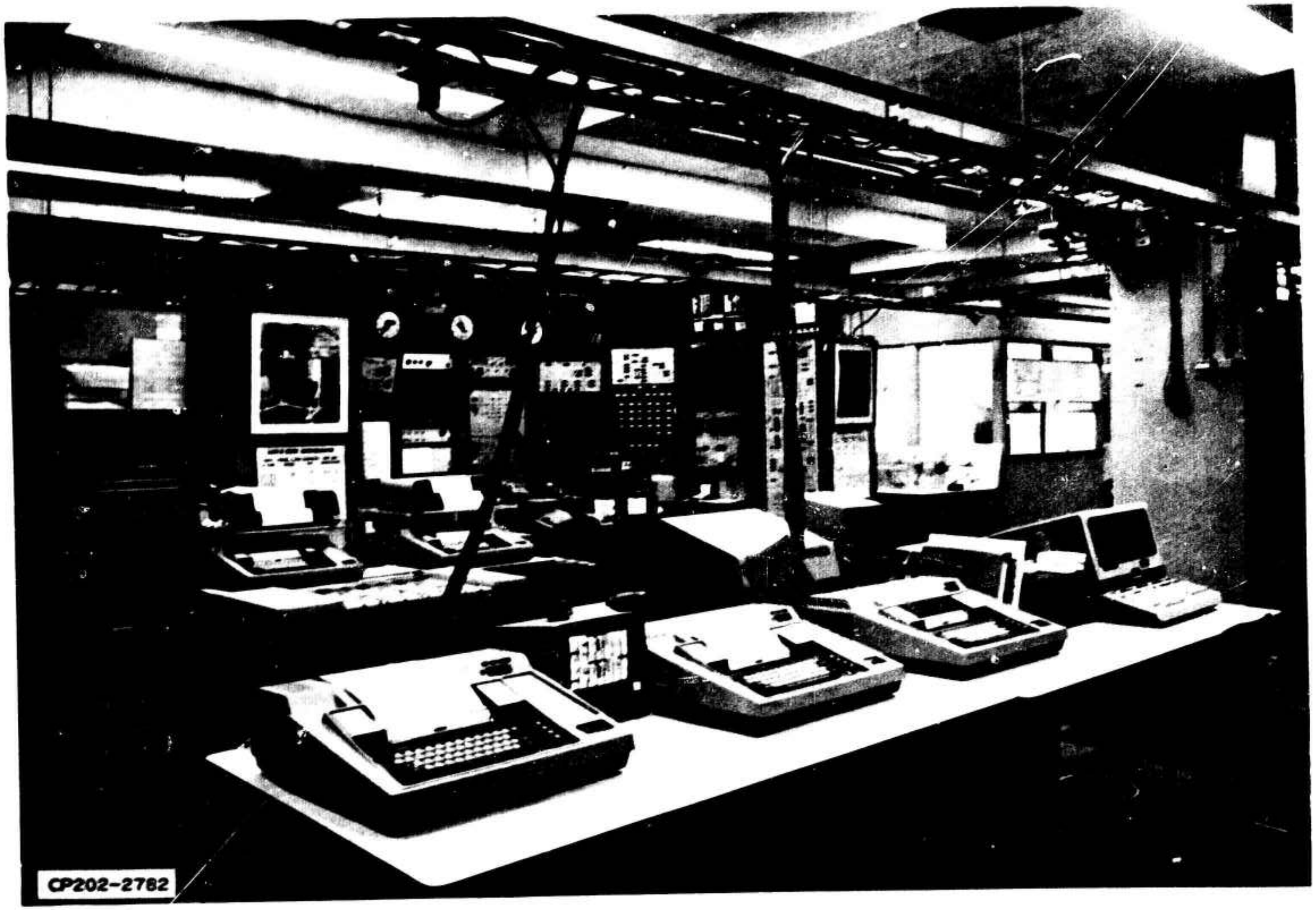


Fig. 52. Interior view of [illegible] 50 and 51.

Fig. 33. Status and control panels in LESOC for the communications systems of LES-8 (left) and LES-9 (right). A panel shown in Fig. 28 is at the top of each rack. CRT displays such as Fig. 29 are presented on the two terminals to the left of the racks, with telemetry data and ephemeris information processed by the minicomputer in the righthand rack.

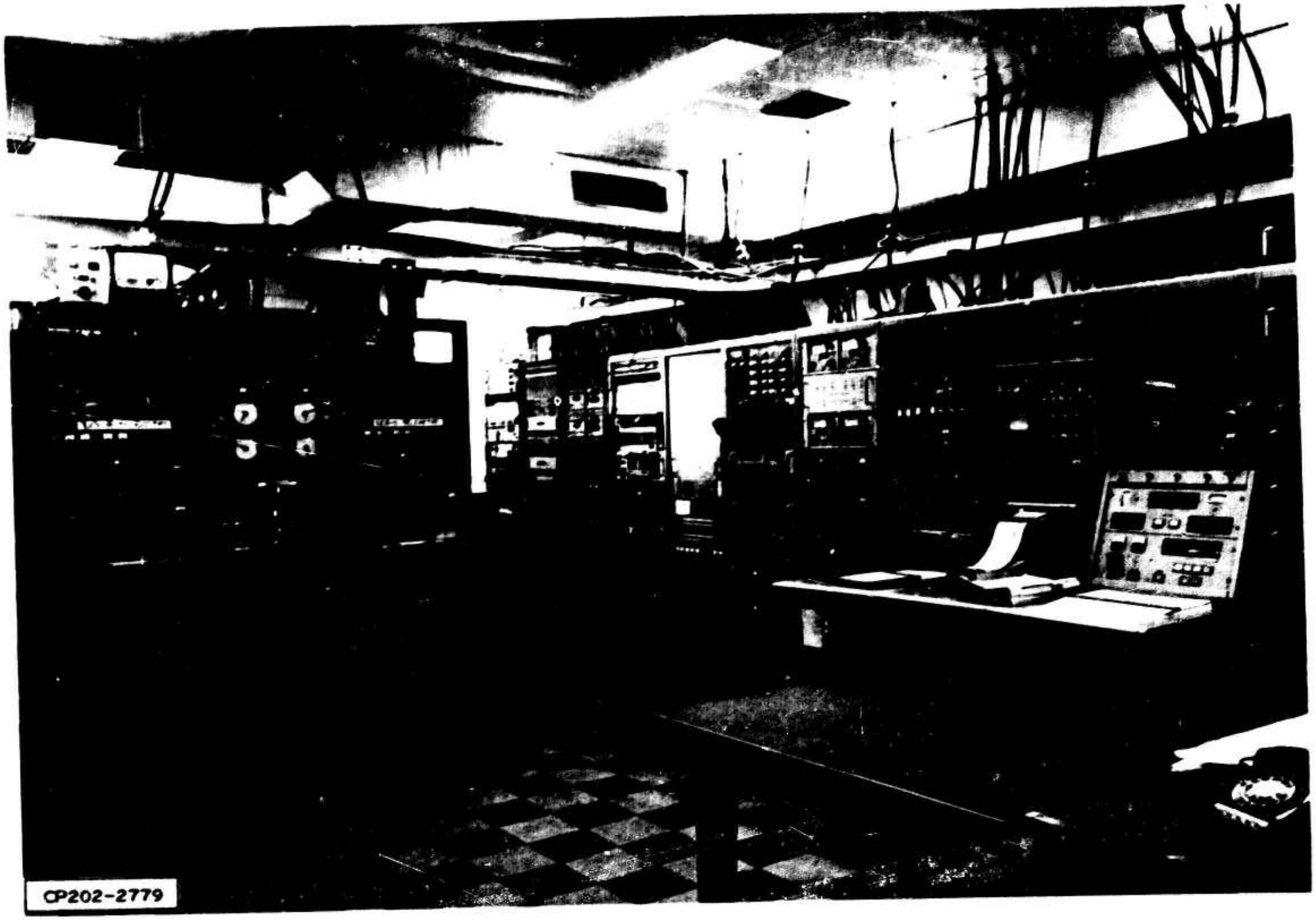


Fig. [illegible]. Interior of Room B-221 at Lincoln Laboratory. The telemetry receivers, the command transmitters, and the associated tracking and fixed-pointed antennas atop Building B are controlled from this room.

telephone system in LESOC, Room B-224, and the communications-terminal penthouse (see Fig. 25) facilitates coordination of operations involving the separate areas. These specialized facilities initially proved their worth during the pre-launch test program.

A control facility that must handle a variety of satellite-support operations, perhaps with frequent transitions between different test activities, might be better served by general-purpose rather than special-purpose displays and consoles. The principles of accessible information presentation and convenient human-operator/machine interaction that are found throughout LESOC could and should be applied throughout such a facility, however.

XII. OPERATIONAL CAPABILITY

Following the conclusion of the formal LES-8/9 Joint Test Program, LES-8/9 were transferred as residual assets to the custody of the Air Force Communications Service (AFCS). The day-to-day scheduling and allocation of satellite resources (specifically, the communications functions) is carried out by the Tactical Relay Operations Center (TROC) of AFCS at Brandywine, Maryland. The actual technical control of the satellites' housekeeping and communications systems continues to be exercised by Lincoln Laboratory from LESOC (Sec. XI).

The principal use of the satellites in this operational-capability phase of their lives in orbit (name: SCOPE DAWN) is as standard, frequency-translating, filter-plus-hard-limiter, UHF-to-UHF transponders (similar to LES-5, LES-6, TACSAT-1, and the three Gapfillers). That capability was provided for in the early stages of the design of LES-8/9, in recognition of the likelihood that they would probably be useful someday in that communications mode. LES-9 is in demand for this service, but LES-8 is not, since the LES-8 500-kHz-wide UHF transponder has the same uplink and downlink frequency allocations as do the similar UHF transponders on the three Gapfillers (Fig. 35). To minimize RFI problems, LES-8 is operated in the UHF-transponder mode only under special circumstances. Most of the time, it is available for general test purposes in its advanced-modulation modes.

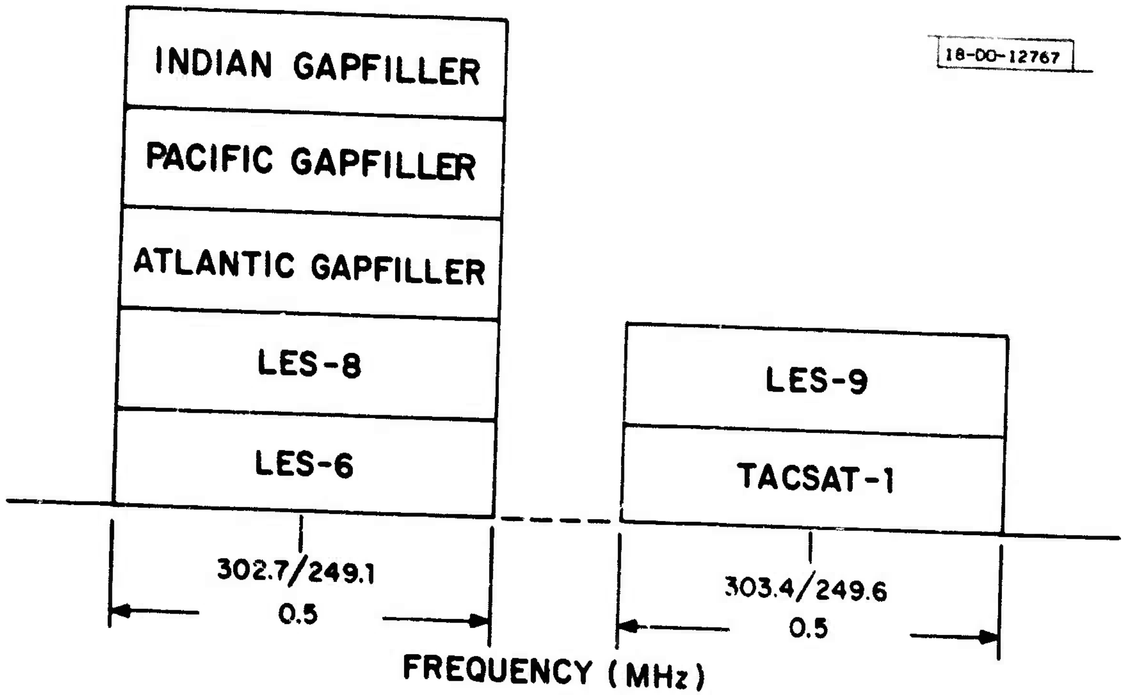


Fig. 35. Uplink/downlink UHF transponder channels.

In the very long term, after the Atlantic and Pacific Gapfillers are no longer providing transponder service, LES-8 might be turned to for this function. As discussed in several succeeding sections, LES-8/9 have the potential of quite long useful lives in orbit. Only a few terminals capable of using the LES-8/9 advanced-modulation format were built for the Joint Test Program. As additional terminals having that capability are procured, LES-8/9 could support communications links that provide the significant AJ capability that has been demonstrated.

XIII. ELECTRICAL POWER

All electrical power for operating LES-8/9 is supplied by a pair (for each satellite) of RTGs. These units were developed by AEC/ERDA/DoE under the multi-hundred-watt (MHW) program (Ref. 25). The original design of these RTGs was based on the requirements of the NASA Voyager (formerly Mariner Jupiter/Saturn) -1, 2 missions for exploration of the outer planets. The RTGs offer impressive advantages of physical survivability by comparison with solar-cell arrays, so ways were found to adapt the design of the LES-8/9 power-conditioning system to the characteristics of the RTGs. For example, the design bus voltage (maximum-power point) for paralleled RTGs is 30V (used in the Voyagers). However, the LES-8/9 design bus voltage is 26V, set by the availability of proven circuit designs. Allowance had to be made for this difference. The Voyager RTGs (which differ in construction only slightly from the LES-8/9 RTGs; three are used on each of the NASA spacecraft) experience a thermal environment that changes only very slowly throughout all but the planetary-encounter phases of the missions. The output power from the Voyager RTGs therefore changes only very slowly also. On the other hand, the LES-8/9 RTGs go through daily double cycles of significant heating and cooling as the three-axis-stabilized satellites rotate once per day relative to the Sun (Ref. 26). The power available from the LES-8/9 RTGs varies accordingly, making more difficult the construction of an analytical model of RTG performance and long-term degradation. Nevertheless, GE (contractor for the MHW RTGs) and JPL (builder of the Voyagers) have developed such models, validating them by comparison with in-flight data from LES-8/9 and the two Voyagers (which were launched in 1977 August and September). Figure 36 shows GE and JPL predictions of available power (daily average value) for the first decade of life for a pair of LES-8/9 RTGs. There will be quite a bit of power left long after that time, given that the assumptions on which the models are based continue to be true.

Figures 37 and 38 show the trend curves for the daily maximum and minimum powers available from the LES-8 and LES-9 RTGs, respectively. These Figures commence at orbital insertion (1976 March 15). The last dotted points are for 1978 December 31, 1020 days later. Most of the large positive- and negative-going spikes in these Figures are spurious; artifacts introduced by a too-simple-minded algorithm that scans the telemetry data base for daily maxima and minima. They should be disregarded. The occasional displacements of the trend lines by as much as a watt or so, persisting for several days or longer, correspond to commanded load-switching operations. When a sizable load is taken off the RTG bus, for example, the small positive series impedance of the voltage limiters causes the bus voltage to rise by a fraction of a volt, with a corresponding increase in the power at the bus.

XIV. PROPULSION FOR ATTITUDE AND ORBIT CONTROL

The cold-ammonia gas-propulsion subsystems (GPSSs) for attitude and orbit control have worked very well. We have been frugal in using fuel. A plot of cumulative fuel expenditure for LES-9 since launch is shown in Fig. 39. Comparison with LES-9 longitude data in Fig. 18 is instructive. The impulse-like thrusts for orbit control produce step-function jumps in Fig. 39, connected by ramps corresponding to occasional momentum-dumping in response to the needs of the attitude-control system (ACS). The slopes of the ramps are different in some places, depending on whether the ACS calls for thrusting in both pitch and roll/yaw or in roll/yaw only.

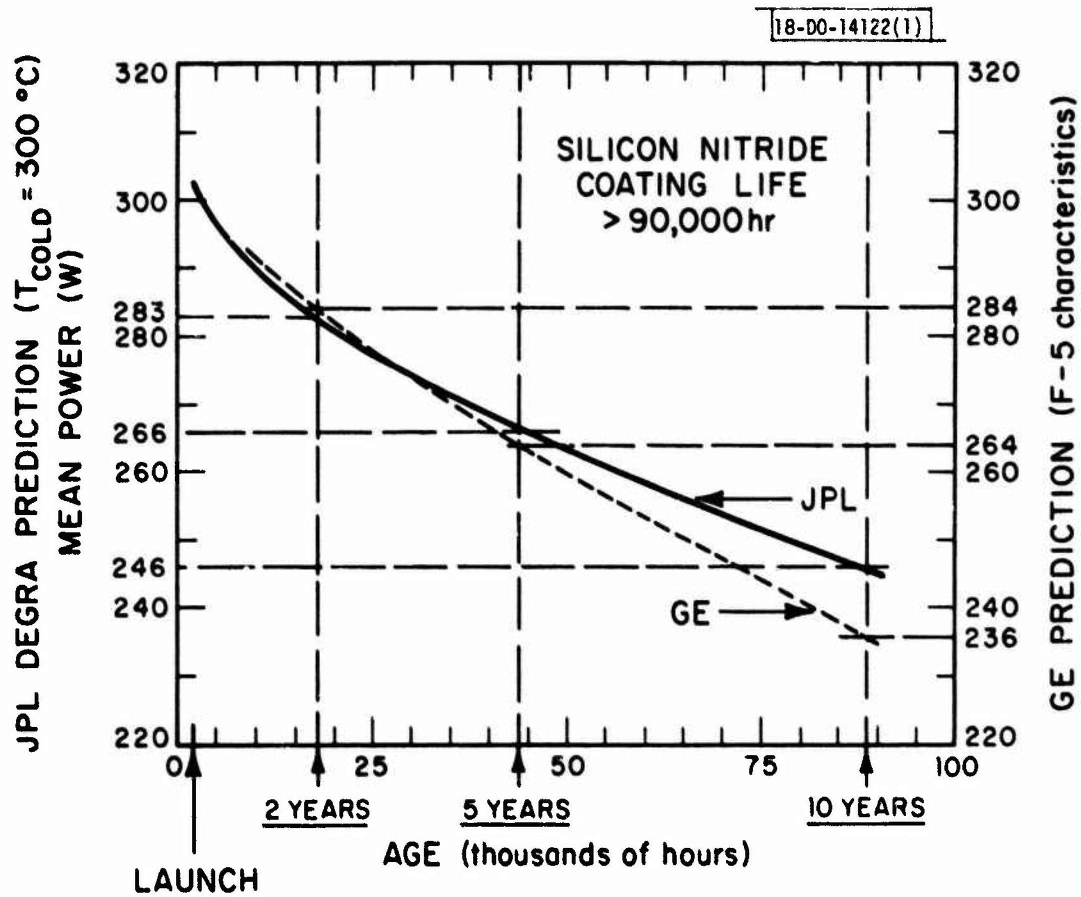


Fig. 36. Predicted output-power profiles for a pair of LES-8/9 RTGs.

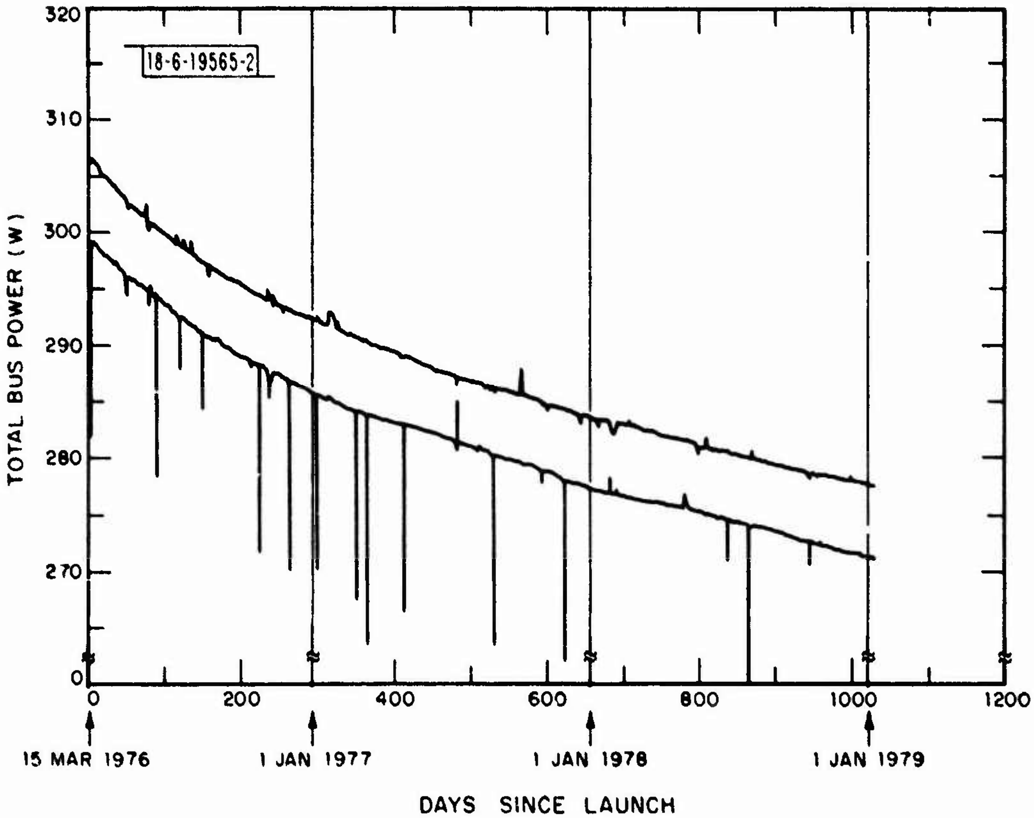


Fig. 37. Daily maximum and minimum RTG output powers for LES-8.

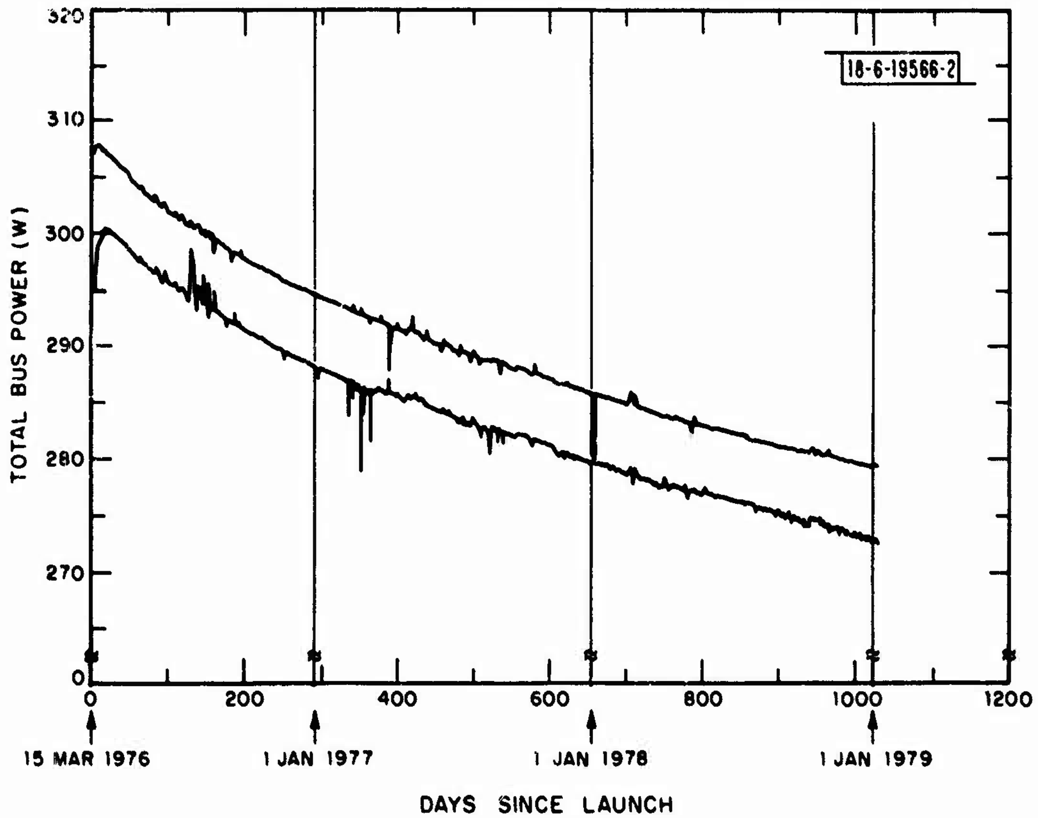


Fig. 38. Daily maximum and minimum RTG output powers for LES-9.

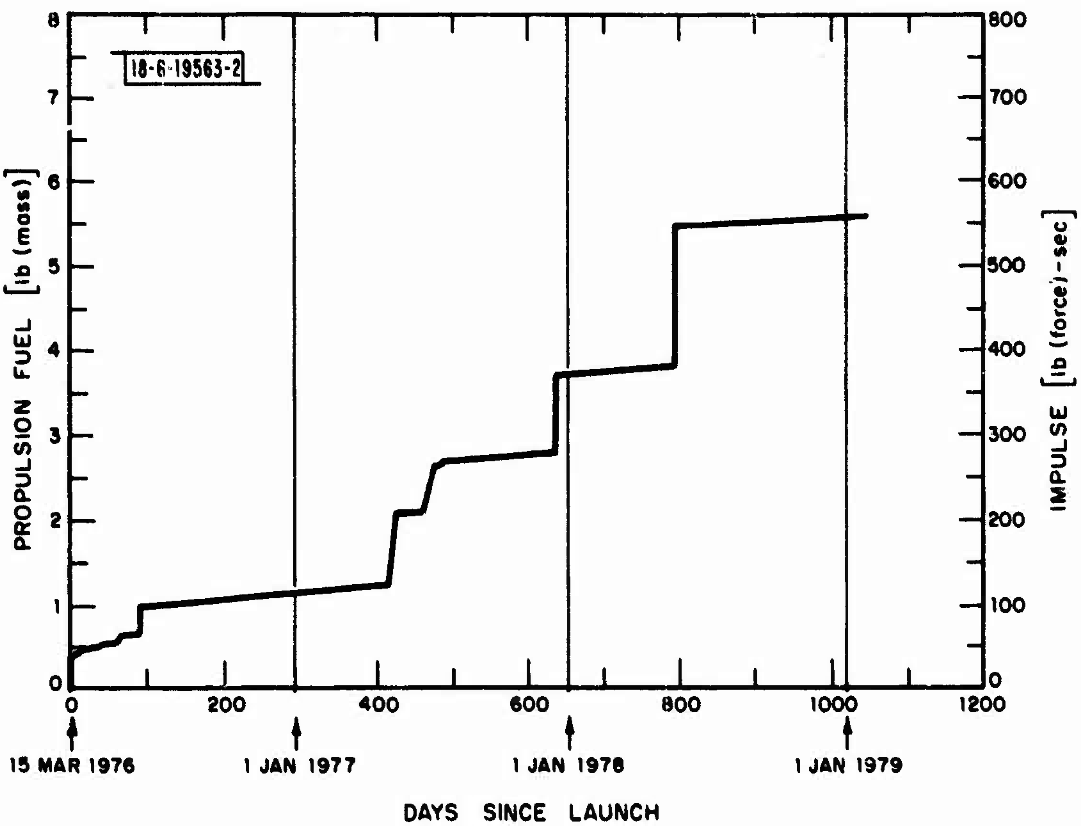


Fig. 39. Cumulative use of propulsion fuel by LES-9. Initial supply: 75 lb (mass).

The fuel ledger for LES-8/9 is as follows:

	LES-8 Fuel (lb (mass))	LES-9 Fuel (lb (mass))
Initial loading (launch, 1976 March 15)	74.00	75.00
Usage to 1979 January 15	7.51	5.58
Remaining	66.49	69.42

The impulse scale of Fig. 39 is related to the mass scale and to the numbers above by the specific impulse of ammonia as used in the LES-8/9 GPSS. I_{sp} = 100 lb (force)-sec/lb (mass). At their present nominal stations (Fig. 20), the fuel requirement for stationkeeping LES-8/9 is comparatively low. There is ample fuel remaining on board both satellites for long useful lives, even assuming station changes (with corresponding fuel costs to start and stop) to places where the fuel requirement for stationkeeping is much higher.

XV. GIMBALED MOMENTUM WHEEL

The one identifiable single-point-failure component in LES-8/9 is the gimbaled momentum wheel (GMW). This component is a modified Bendix Vela wheel, turning at speeds between 990 and 1330 rpm. It serves the dual functions of a reaction wheel for pitch control and a control-moment gyro for roll/yaw control. It also serves as an active nutation damper. The GMW motor is fed by alternative inverters and can be controlled using backup modes of the ACS, but it has no backup bearings. If the bearings go to pot, attitude control is swiftly lost and the satellite ceases to be useful. Consequently, the state of the GMW bearings is of considerable interest. It can be ascertained indirectly by examining the telemetered values of motor power for the same wheel speed and temperature. A degradation of bearing performance would be indicated by increased wheel-power consumption for the same speed and temperature.

Scrutiny of the data since launch (2+ years in orbit) shows no evidence of degradation of the GMW bearings on either LES-8 or LES-9. It appears that the LES-9 GMW bearings "ran in" during the first year, for the motor power decreased somewhat during that interval. Given these favorable indications, we hope for long, troublefree service from the LES-8/9 GMWs.

The operation of the LES-8/9 ACSs in orbit has been highly satisfactory. The GMW control system (GMWCS) and the ACS have operated in the autonomous mode almost all the time since insertion into final orbit and initial Earth-lock. LESOC is not manned around the clock. Each satellite controls its own attitude without intervention from LESOC. Thrusting for momentum-dumping is done automatically.

The precision scanning IR Earth sensors (built by TRW Systems) carried by LES-8/9 provide essentially continuous readout of pitch and roll for the satellite in or near Earth-lock. If it is desired to measure yaw in a similarly unequivocal way, that can be done by bringing up the inter-satellite crosslink (Fig. 40). Complete measurement of satellite attitude in orbit (3 Euler angles, for example) by this method has been helpful in studying the diurnally varying torque effects of the solar radiation incident on the satellite.

XVI. BONUSES

During the prolonged gestation of LES-8/9, faint-hearted onlookers sometimes asked whether any satellite that complicated could ever be made to work. Our instant optimistic affirmations have been amply justified by the resounding success of LES-8/9 in orbit. However, it was reassuring in those strenuous days to be able to remind the onlookers that LES-8/9 would have so many features, alternatives and backup modes, that it was virtually certain that something would work, and highly likely that many things would. Happily, everything worked.

Now, with 2+ years of LES-8/9 experience in orbit behind us, and having found respite for reflection, we perceive another favorable aspect to the complexity of these satellites. They have so many features, alternatives and

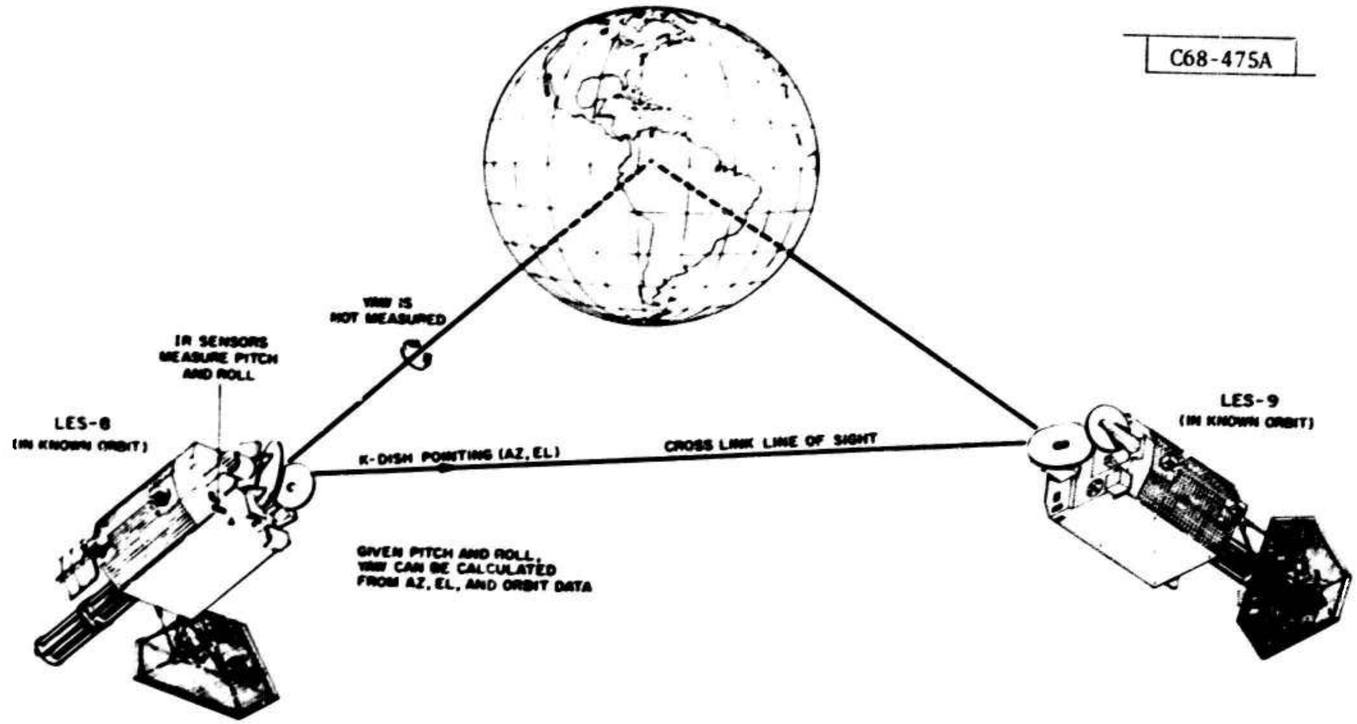


Fig. 40. Complete determination of satellite attitude.

backup modes that they can do some things that were not advertised before launch, or even appreciated then. For example (Figs. 41 and 42), the hopped uplink local oscillator can be set by command so that the satellite listens at just about any frequency over a broad stretch of the military UHF band. Instrument-quality power-measurement circuitry in the uplink receiver then gives readings which are telemetered to LESOC. Reduction of an extended collection of that data yields a statistical analysis of spectrum occupancy by terrestrial terminals. This technique is a significant advance over the less-flexible RFI-measurement experiments of LES-5 and LES-6 (Refs. 27 and 28).

XVII. LONG LIFE IN ORBIT

How long will LES-8 and LES-9 be useful? Before attempting to answer that question (Table 4), we must rule out chance catastrophes such as collisions with cosmic debris and ruinous operating mistakes in LESOC (wasting all the propulsion fuel, for example). The RTG power sources are degrading gracefully (Section XIII). The propulsion fuel has been and is being used frugally (Section XIV). The GMW bearings continue to look good. It has been possible to work around the few subsystem failures that have occurred during 2+ years in orbit. However, there may come a time when the backup provisions for some absolutely essential subsystem have been exhausted. At that point the cheese will bind. Until then, each satellite will remain useful, perhaps for decades.

TABLE 4

LIMITING FACTORS FOR LES-8/9 LIFE

RTG Power Degradation

Propulsion Fuel Expenditure
- Attitude Control
- Orbit Control
  - Stationkeeping
  - Station Changing

Critical Component Failures
- Gimbaled Momentum Wheel

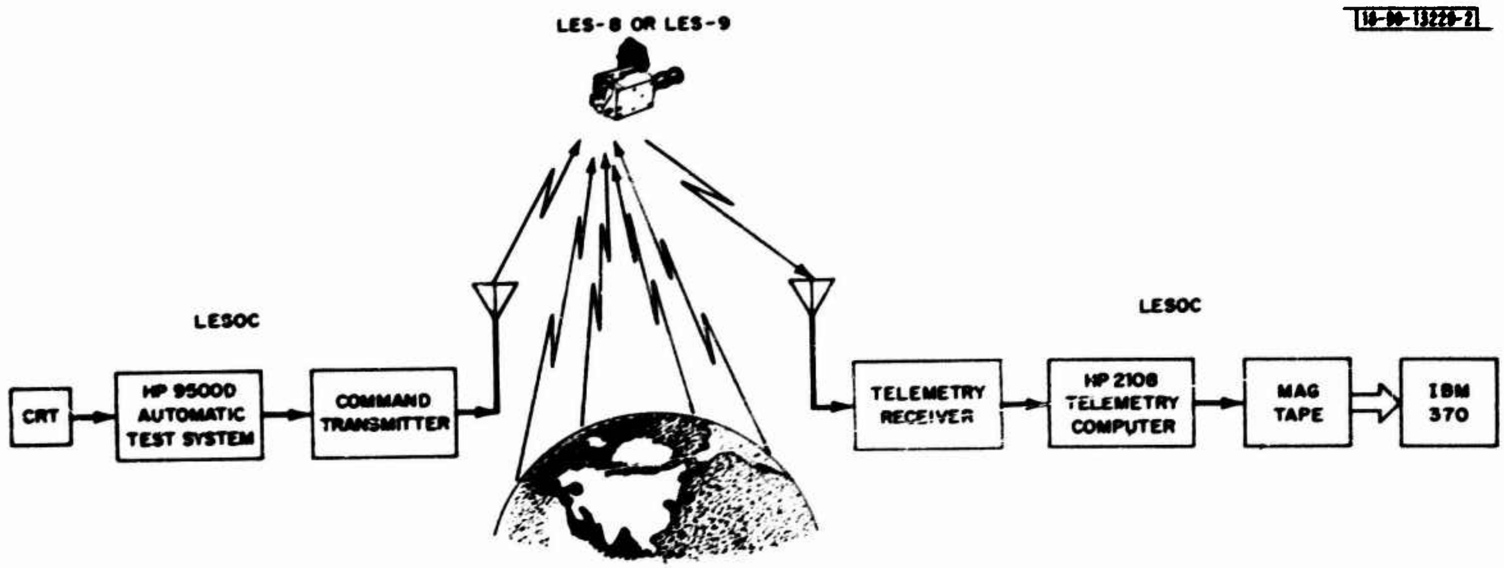


Fig. 41. Spectrum survey by LES-8 or LES-9.

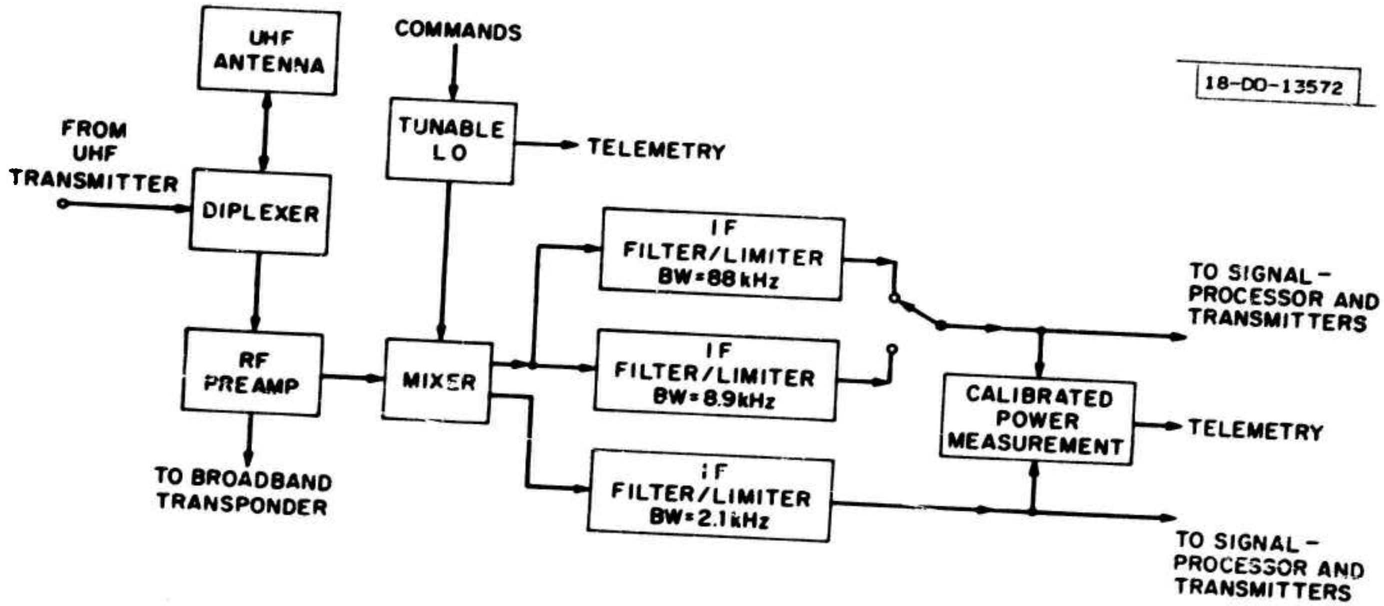


Fig. 42. UHF spectrum survey by LES-8 or LES-9.

Can that failure point be predicted on a statistical basis? Lincoln Laboratory believes that it can not. There is a prediction procedure (often required by contract specifications) that involves calculating the mean mission duration, say, based on the parts count, the degree of redundancy employed, and **assumed** failure phenomena that are random in time and have a nearly constant rate (Poisson statistics). It is our belief that this mathematical exercise bears little relation to observed reality. The postulated failure models are simply inconsistent with what actually happens. Others have made the same observation. Pilcher (Ref. 29), reviewing the experience of a major aerospace firm that has built many successful communication satellites, says:

> "... in-orbit experience .... suggests that most, if not all, such failures are generic to the design or construction of the particular element of the satellite. Thus if one unit fails in a particular manner, its redundant counterpart will likely fail in the identical manner. The fortunate corollary is that once the failure mechanism can be identified, subsequent satellites can be modified to eliminate it ....
>
> "If our experience is accurate, random failure model predictions of satellite life may be grossly pessimistic - provided one has a satellite based on design proven in orbit."

LES-8/9 were delivered for launch after protracted and rigorous ground testing. This testing verified the general high quality of their design and the workmanship of their manufacture, and it pointed out some areas where improvement was called for. Experience in orbit to date indicates that spacecraft of this or higher degrees of complexity can be developed and used with good confidence in their success.

ACKNOWLEDGMENT

It has been said of the Moors, architects of the Alhambra (Granada, Spain, constructed 1248-1354 AD) that they built like giants and finished like jewelers. The LES-8/9 enterprise was indeed gigantic. It was successful because of the devoted efforts of many people, outside Lincoln Laboratory as well as inside, who strove for jewel-like perfection in the details of the design, construction, and testing (both pre- and post-launch) of the spacecraft and the terminals. It is not feasible to name them here. This report is a tribute to their remarkable accomplishment.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ABNCP	Airborne command post
ACS	Attitude-control system
A/D	Analog-to-digital (signal conversion)
AEC	Atomic-Energy Commission
AFAL	Air Force Avionics Laboratory
AFCS	Air Force Communications Service
AFSC	Air Force Systems Command
AIAA	American Institute of Aeronautics & Astronautics
AJ	Anti-jam
ATS	Applications Technology Satellite (NASA)
ATS	Automatic test system
AZ	Azimuth
BCD	Biaxial cross-link drive
C^3	Command-and-control communications
CIT	California Institute of Technology
CMD	Command
CRT	Cathode-ray tube
CSDL	Charles Stark Draper Laboratory
DAY	Dayton, Ohio
DC	Direct current
DoD	Department of Defense
DoE	Department of Energy
EHF	Extremely-high frequency, 30-300 GHz
EL	Elevation angle
ERDA	Energy Research & Development Administration
ESD	Electronic-Systems Division, AFSC
ESI	Electrospace Systems, Inc.
FE	Force element
FET	Force-element terminal
GE	General Electric Company
GMW	Gimbaled momentum wheel
GMWCS	Gimbaled-momentum-wheel control system
GPSS	Gas-propulsion sub-system
GSFC	Goddard Space-Flight Center, NASA
HP	Hewlett Packard
IBM	International Business Machines Corporation
IC	Integrated circuit
IF	Intermediate frequency
INTELSAT	International Telecommunications Satellite Consortium
IR	Infrared, the optical spectrum in the approximate range 0.7 – 300 μm
IRS	Infrared sensor
JANNAF	Joint Army/Navy/NASA/Air Force
JPL	Jet Propulsion Laboratory, CIT
K-band	Frequencies in the range 20 - 40 GHz; 36 - 38 GHz for LES-8/9
LC	Launch complex
LCC	Launch-control center

LED	Light-emitting diode
LES	Lincoln Experimental Satellite
LESOC	Lincoln Experimental Satellite Operations Center
LL	Lincoln Laboratory
LO	Local oscillator
MFSK	Multiple frequency-shift keying (modulation, demodulation)
MHW	Multi-hundred-watt (RTG development program)
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NELC	Naval Electronics Laboratory Center, now NOSC
NOSC	Naval Ocean-Systems Center
NRL	Naval Research Laboratory
OSR	Optical solar reflector
PC	Printed circuit
PEP	Planetary-ephemeris program
PPT	Pulsed plasma thruster
P74-1	STP Titan-IIIC launch carrying LES-8/9
PVLIM	Power in voltage limiter
PWRST	Power-system status
RF	Radio frequency
RFI	Radio-frequency interference
ROM	Read-only memory
RTG	Radioisotope thermoelectric generator
S-BAND	Frequencies in the range 1.55 – 3.90 GHz
SAB	Spacecraft Assembly Building (Cape Canaveral)
SAMSO	Space & Missile Systems Organization, AFSC
SK	Stationkeeping
SOLRAD	NRL-built spacecraft launched with LES-8/9 on same booster
STP	Space Test Program (SAMSO office)
TACAMO	Navy airborne radio-relay platform ("Take charge and move out.")
TACSAT-1	Spacecraft supporting tactical satellite communication
TDRSS	Tracking and data-relay satellite system
TGG	Third-generation gyro
TGGS	Third-generation-gyro system
TLM	Telemetry
TMF	Test-Management Facility, ESD
TROC	Tactical Relay Operations Center, AFCS
TRW	Thompson Ramo Wooldridge/TRW Systems
TWX	Teletypewriter exchange
UHF	Ultra-high frequency, 300 – 3000 MHz; also military communications band, 225 – 400 MHz
VAFB	Vandenberg Air Force Base, California
WOM	Write-only memory

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This report presents a number of sidelights on the development, testing, and operation in orbit of Lincoln Experimental Satellites 8 and 9 (LES-8/9). The details of these matters have been published elsewhere. Significant factors contributing to the success of the LES-8/9 program (terminals as well as satellites) are identified.

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